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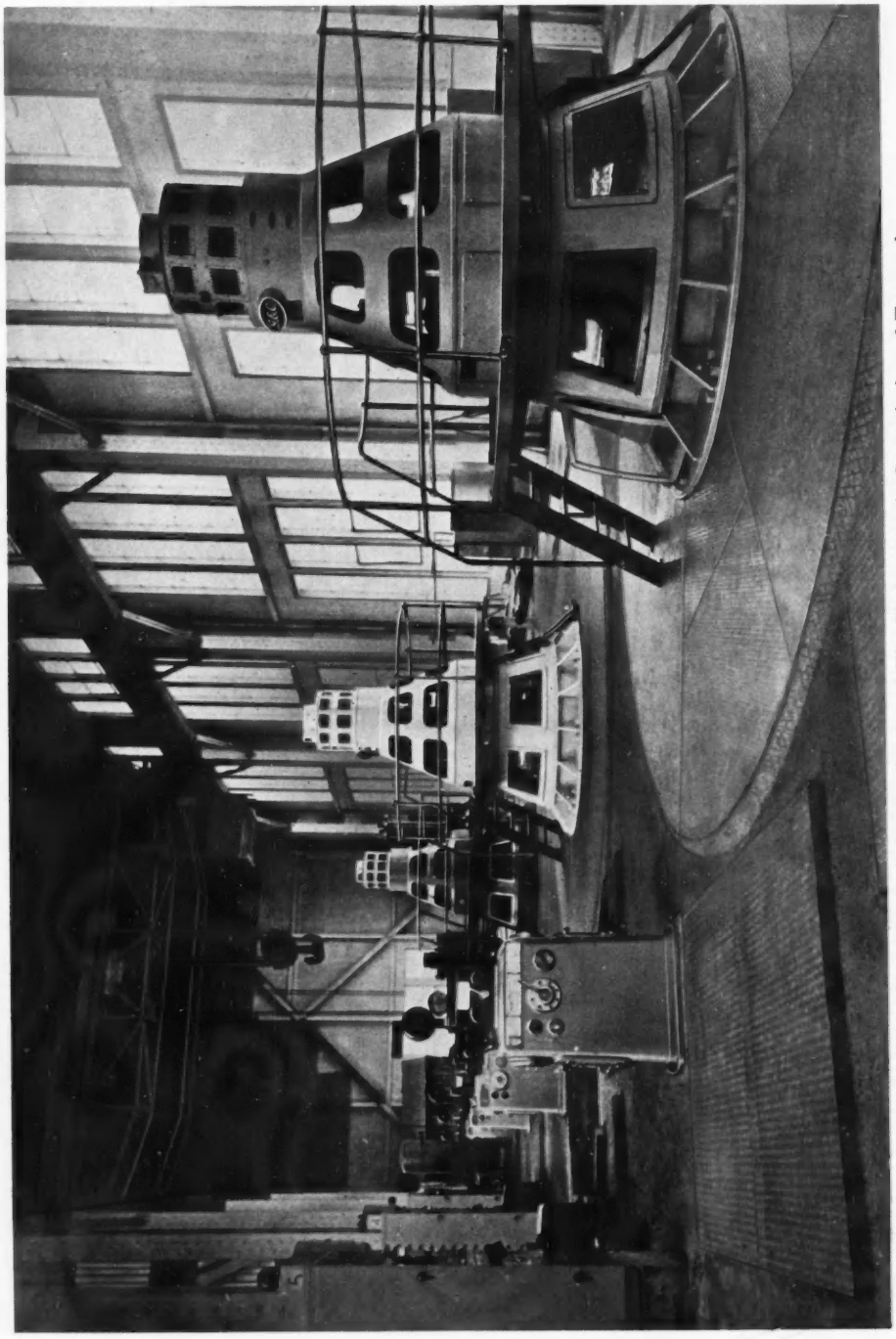


Interior of the Tungatinah Power Station of The Hydro-electric Commission of Tasmania.

Hydro-electric Plant at Tungatinah Power Station

By H. L. BARNARD, B.E., M.I.E.E., M.I.E.Aust., A.M.I.Mech.E.,
Chief Electrical Engineer, British General Electric Co. Pty. Ltd., Australia.

TASMANIA, an island rich in beauty and possessing great mineral wealth, particularly in the western section, is essentially a water power country. Its lakes and rivers afford potential power approaching 3½ million horsepower (at fifty per cent load factor). Since the population of Tasmania is less than 350,000 persons, the potential power of more than 10,000 horsepower per 1,000 head of present population must rank as one of the highest in the world.

The development of water power dates from 1892 when the Launceston City Council began work on the Duck Reach Scheme on the South Esk river, and three years later on December 10th, 1895 electric lighting became available in the city. Since that date, the use of water power has progressed at an ever-increasing rate, culminating in the development of the Derwent Catchment Area. This huge project (fig. 1) comprehends the Great Lake Power Development which includes the Shannon and Waddamana Power Stations, and Power Development Schemes for the Butlers Gorge, Tarraleah, Tungatinah, Lake Echo and Wayatinah Power Stations.

TUNGATINAH POWER DEVELOPMENT.

It is with the first stage of the Tungatinah scheme, which includes the commissioning of the Tungatinah Power Station, that this article is particularly concerned. For this station, contracts were placed by The Hydro-electric Commission of Tasmania with The British General Electric Co. Pty. Ltd., Australia for five 25 MW alternators. The first set was officially switched on to the electrical network on June 30th, 1953, and since then two further machines have been brought into service. Exterior and interior views of the Power Station are shown in fig. 2 and in the frontispiece.

Two and a half miles upstream from the Lyell Highway the Pine Tier Dam has been built across the Nive River to create a new lake and divert the flow through eight miles of concrete flumes and canals to the Bronte Lagoon. From there, the water is led by canals and cuts to the artificial storages, Bradys Lake and Lake Binney, whence it flows into the Tungatinah Lagoon. A tunnel with a cross section of 231 sq. ft. has been driven through the hills to supply five steel penstocks each 3,200 ft. long and of maximum diameter of 90 inches, which lead to the power station.

The construction of the Pine Tier Dam, which is 120 ft. high, taps a catchment area of 321 square miles having an average annual run-off of 590 cusecs. A weir, constructed across the Clarence River, diverts additional water to Bronte Lagoon through a wood stave and steel pipeline, 5½ miles long and 63 inches diameter, having a capacity of 190 cusecs. A small dam will be built later across Laughing Jack Lagoon to provide some storage for regulation of the catchment area of 48 square miles. The average flow diverted to Bronte Lagoon will be 120 cusecs.

Finally, on the completion of the second stage of the scheme, which includes the provision of storage at Lake Echo, the construction of Lake Echo Power Station and the diversion of the River Dee, a further source of water supply will be available for the Tungatinah Station. A rock and earth fill dam, 60 ft. high, is being built across the outlet from Lake Echo. This natural lake has a surface area of 11 square miles and the total storage available will be 600 square mile/feet. The headwaters of the Little Pine and Ouse Rivers will be diverted into Lake Echo and a canal, having a capacity of 800 cusecs, will lead from the lake to a steel penstock of diameter 114 in., which will supply Lake Echo Power Station. A dam, 50 ft. high, being built across the Dee River adjacent to the Lyell Highway, will create an artificial lake below the power station, to be known as Dee Lagoon.

From here a 2¼-mile tunnel of 800 cusecs capacity will carry the water to Bradys Lake and thence to Tungatinah Power Station. The catchment area below Lake Echo to be brought into service by the dam covers 51 square miles and has an average annual run-off of 50 cusecs.

GENERATING PLANT.

The generating plant consists of five alternators each rated at 31·25 MVA, 25 MW, 0·8 p.f., 11 kV, 3-phase, 50 cycles, 600 r.p.m. Each alternator is of the vertical shaft type with a combined thrust and guide top bearing and a bottom guide bearing, the former being supported on a bracket mounted on the frame of the alternator. Mounted above the alternator and directly coupled to it are the main exciter, pilot exciter, and permanent magnet governor alternator, the three machines being assembled to form a self-contained unit.

The complete machine is driven by a directly coupled Francis turbine of Boving manufacture rated at 35,000 h.p. and operating under a static head of 1,005 ft., the set being designed for an overspeed of 1,050 r.p.m.

In order to comply with transport requirements, the alternators, which weigh over 175 tons, were constructed in such a manner that the weight of any single part was limited to 35 tons. The stator was split and despatched in two

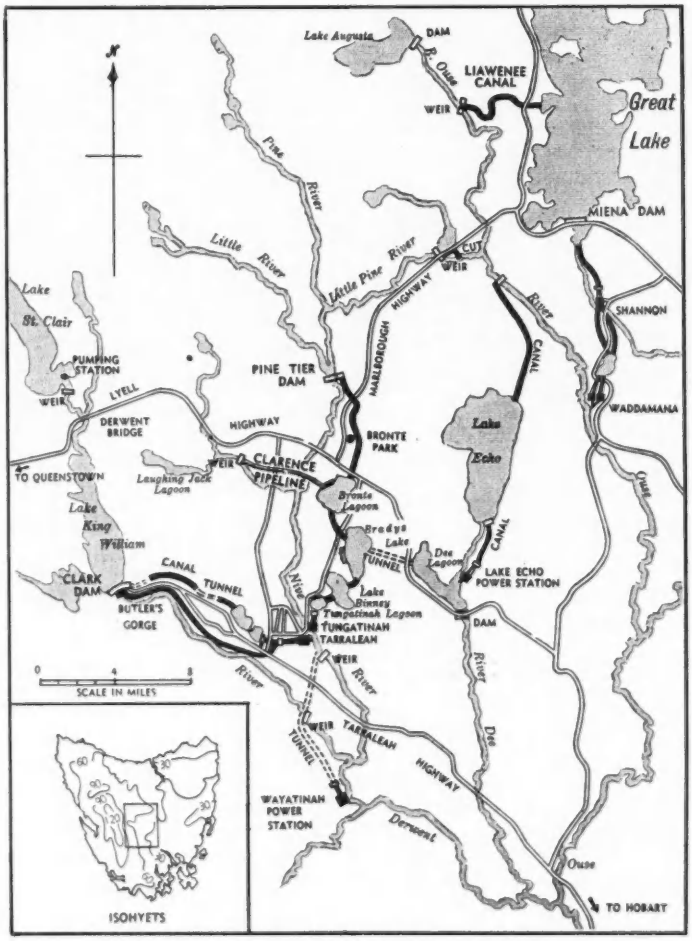


Fig. 1.—Hydro-electric development of the River Derwent and tributaries.

halves, poles with their field coils were removed from the magnet wheel, the exciter armatures and permanent magnet alternator rotor formed a self-contained assembly, while the radial arms supporting the top thrust bearing housing were also dismantled and shipped separately.

bottom of the frame. Views of the stator in course of winding and completely wound are shown in figs. 4 and 5. Aluminium guards provide adequate protection of the end windings and serve also to guide the cooling air through the machines.

Fig. 2.—General view of Nive River looking upstream, showing the Tarraleah Station in the foreground and the Tungatinah Station in course of construction in the background.

A sectional arrangement of the alternator, exciters and permanent magnet governor generator is shown in fig. 3.

STATOR.

The stator frame is a heavy fabricated structure of octagonal shape, built in two halves which are bolted and dowelled together. The construction of the core follows standard practice, segmental stampings being secured by dovetailed keys bolted to longitudinal ribs within the frame.

For these machines a two-layer diamond type winding is used, the insulation being of class 'B' category comprising mica and micanite throughout. The end windings are securely strapped to Permali supports fixed to the core clamping plates, the connections being brought out through an insulating plate situated near the

Six thermo-couples, embedded in the stator, enable the temperatures of the core and windings to be recorded on the remote temperature indicator which is mounted on the turbine gauge panel.

ROTOR.

The rotor is designed for a safe overspeed of 75 per cent, i.e. 1,050 r.p.m. The shaft and coupling are forged in one piece. Twelve plates are shrunk and keyed on the shaft to form the rotor body into which the laminated poles are T-slotted and secured by taper keys as shown in fig. 6.

Each pole winding is subjected to heat and hydraulic pressure to form a solid coil in which risk of movement of individual turns is eliminated. Circumferential movement is prevented by duralumin wedges fitted between adjacent

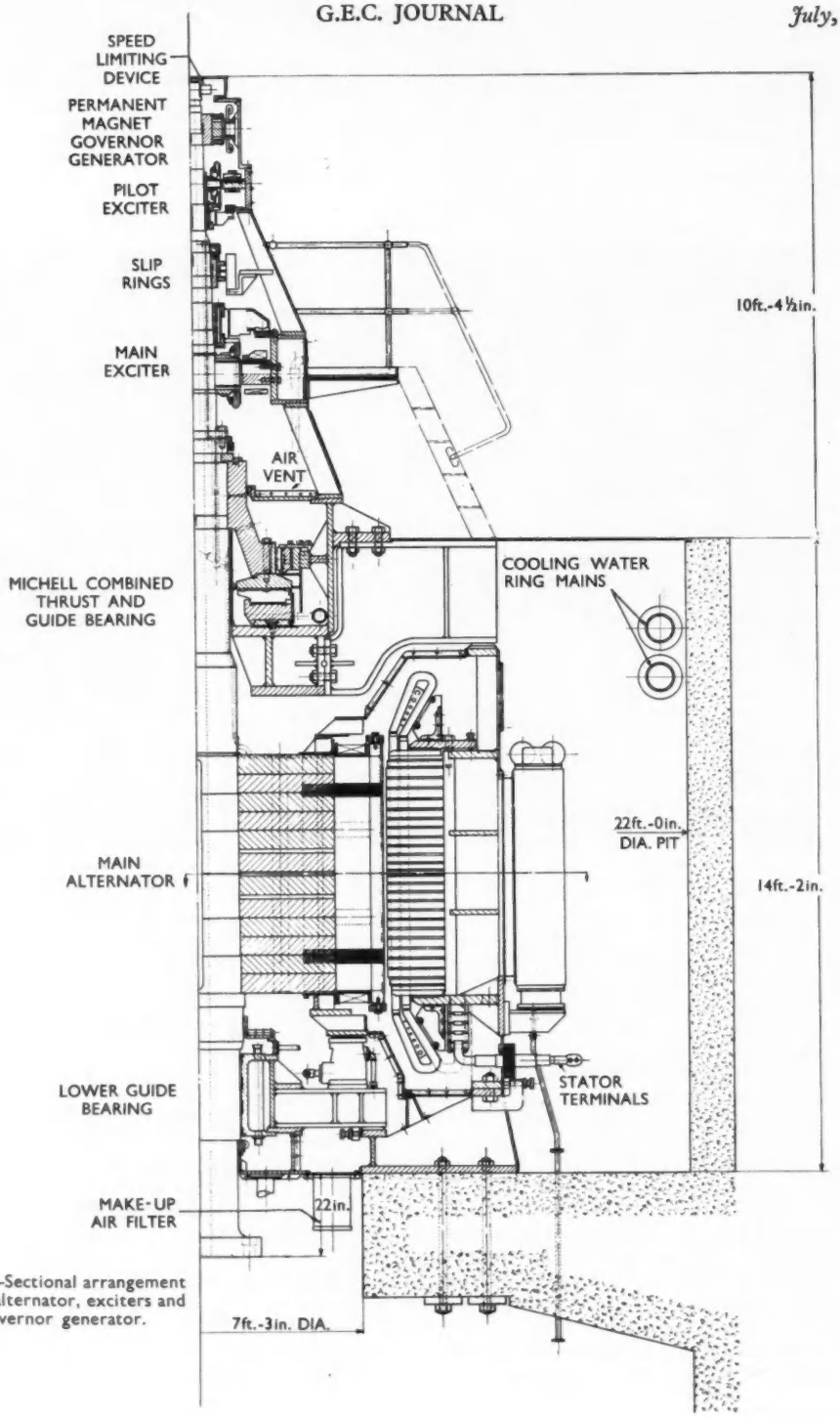


Fig. 3.—Sectional arrangement of the alternator, exciters and governor generator.

Fig. 4.—Stator in course of being wound.

pole windings and secured to the rotor body (fig. 7.)

Copper rods in the pole faces are brazed into copper plates which are connected together by duralumin rings to form the squirrel cage damping winding.

Two centrifugal fans, one at each end of the rotor, circulate the cooling air through the machines, the lower fan embodying the braking ring as seen in fig. 7.

The rotor is supported by a thrust and guide bearing of the Michell type which is designed to carry a total load of 270 tons, representing the weight of the rotor and the external thrust produced by the water turbine. The housing is spigoted and bolted to the thrust bracket assembly which is bolted to the stator frame and located by tapered dowels. Doors in the housing give access to the thrust pads for maintenance purposes. The bottom guide bearing housing is centralised and located by jacking screws, no spigot being used.

In order to obviate any risk of current circulating through the rotor shaft, the thrust and guide bearings are insulated from the supporting structure.

EXCITER ASSEMBLY.

The armatures of the main and pilot exciters, the rotor of the permanent magnet alternator for supplying power to the turbine governor motors, and the centrifugal overspeed device are mounted on a forged steel shaft to form a self-contained assembly (fig. 8.) which is solidly coupled to the main alternator shaft.

The main exciter is separately excited with a counter shunt winding, while the pilot exciter is compound wound, initial adjustment of the field current of this machine being effected by a shunt field regulator.

The brush gear of both exciters and for the alternator sliprings is mounted within a fabricated stool situated between the two exciters

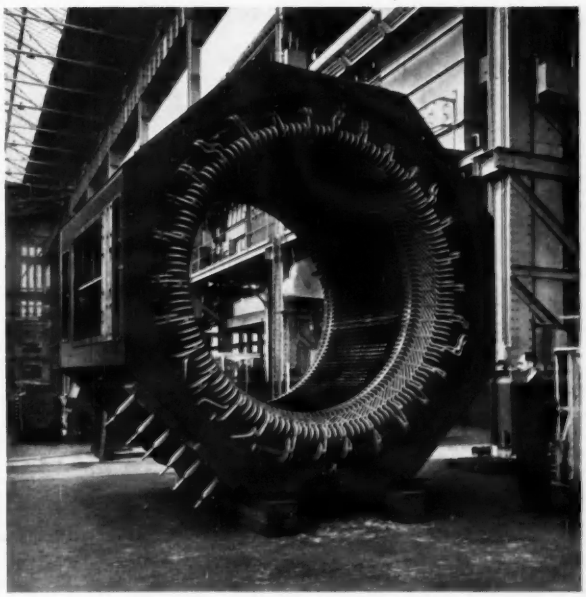


Fig. 5.—Stator completely wound.

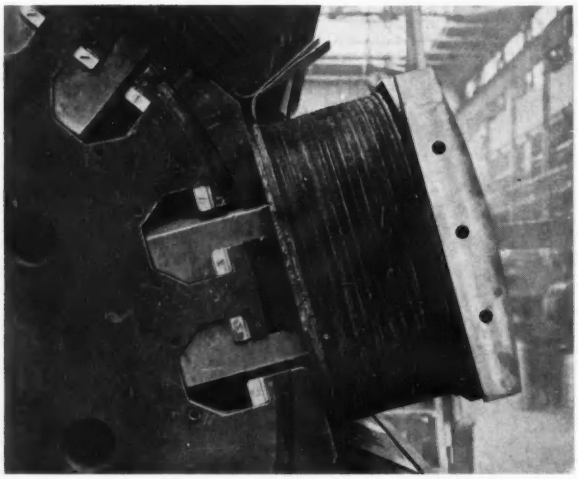


Fig. 6.—Method of securing the poles to the rotor body.

as shown in fig. 3, the brushgear being supported on adjustable yokes. The cupro-nickel sliprings are mounted on an insulated hub which is pressed on and keyed to the shaft, while adequate creepage is given by an insulating barrier fitted between the rings. Doors in the stool give easy access from a raised platform which surrounds the exciter assembly.

VENTILATION.

Reference has already been made to the centrifugal fans which are mounted on the magnet wheel and circulate air through the machine. The cooling system forms a closed air circuit in which cool air is drawn from the alternator pit and forced through the machine, the warm air being returned to the pit through the cooler which is arranged in eight sections mounted around the shell of the machine as seen in fig. 10, which shows the alternator erected on the Works test bed.

Temperature detectors in the air inlet and outlet are connected to a Cambridge instrument on the turbine gauge panel. In addition, two Budenberg mercury-in-steel thermometers, fitted with adjustable maximum contacts, operate alarms if the inlet and outlet air temperatures exceed predetermined values, the thermometer dials being mounted on the turbine gauge panel.

The coolers were designed and manufactured by The Premier Cooler and Engineering Co. Ltd. each cooler section forming a self-contained unit and comprising a nest of tubes around each of which a heat transfer element is wound. Cooling water is supplied from a ring water

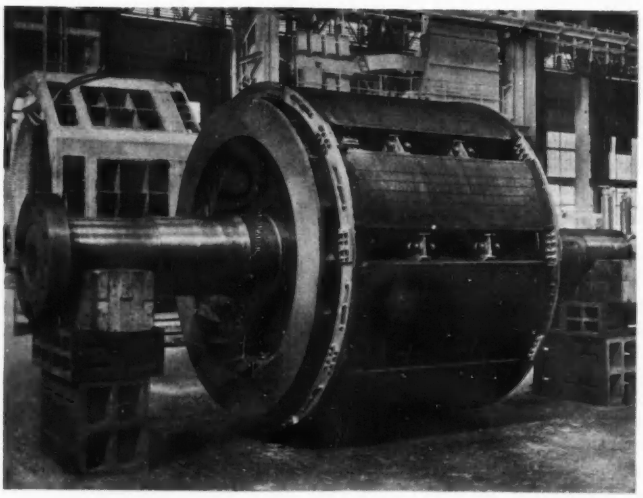


Fig. 7.—Completed rotor showing the combined fan and brake ring.

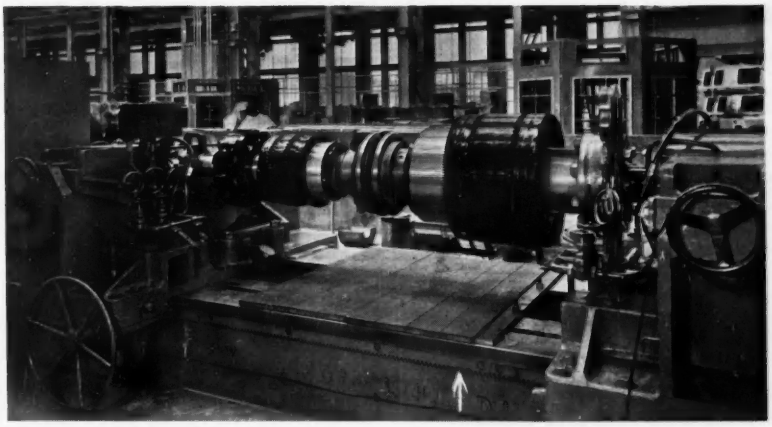


Fig. 8.—Exciter and governor generator assembly in the dynamic balancing machine.

main situated at the top of the alternator pit and consisting of 7 in. dia. inlet and outlet pipes.

With a cooling water inlet temperature of 27 deg. C. and a rate of flow of 616 gallons per minute, the complete cooler assembly will reduce the temperature of 63,000 cu. ft. of air per min. from 56 deg. C. to 35 deg. C. The capacity of each section is such that any seven of the eight units are capable of dissipating the full load losses (approx. 700 kW) so that any one section can be isolated for maintenance purposes with the machines running at full load.

LUBRICATION.

Flow lubrication is used for the guide and thrust bearings of the alternator. Oil from a 1,000-gallon tank is circulated by a motor-driven pump through an Auto Kleen strainer and Serck oil cooler to the bearings, whence it returns by gravity to the storage tank.

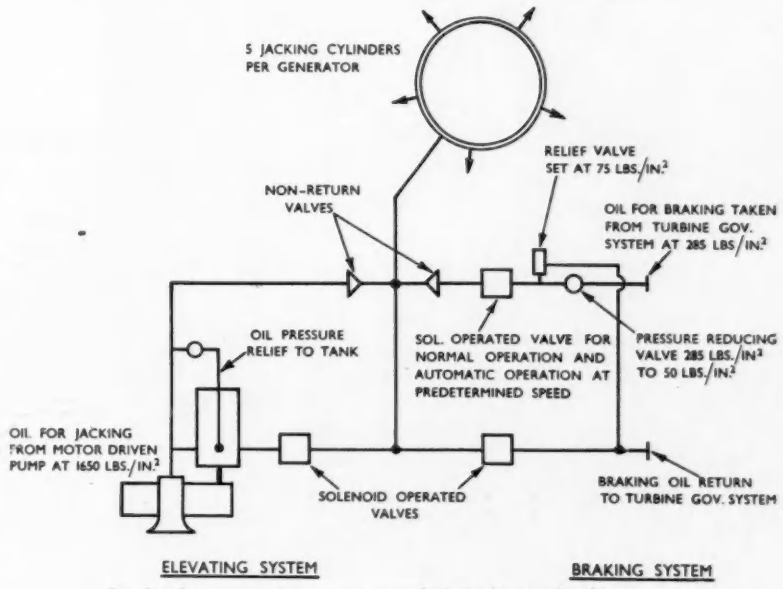

5 JACKING CYLINDERS PER GENERATOR
RELIEF VALVE SET AT 75 LBS./IN.²
NON-RETURN VALVES
OIL FOR BRAKING TAKEN FROM TURBINE GOV. SYSTEM AT 285 LBS./IN.²
OIL PRESSURE RELIEF TO TANK
SOL. OPERATED VALVE FOR NORMAL OPERATION AND AUTOMATIC OPERATION AT PREDETERMINED SPEED
PRESSURE REDUCING VALVE 285 LBS./IN² TO 50 LBS./IN.²
OIL FOR JACKING FROM MOTOR DRIVEN PUMP AT 1650 LBS./IN.²
SOLENOID OPERATED VALVES
BRAKING OIL RETURN TO TURBINE GOV. SYSTEM
ELEVATING SYSTEM
BRAKING SYSTEM

Fig. 9.—Diagrammatic arrangement of the braking and jacking system.

The pump has a capacity of 180 gallons a minute at 75 lb. per sq. in. pressure, and is driven by a 20 h.p., 415 volt, squirrel cage motor. A similar standby pump is provided and is brought into operation automatically by the action of a flow relay should the rate of flow fall below a preset value. As an additional precaution, the standby pump is driven by a 20 h.p. D.C. motor, fed from an independent source of direct current, thereby eliminating any risk of loss of oil to the bearings in the event of a failure of the A.C. supply.

A standby cooler is also installed so that servicing may be undertaken while the alternator is running. Each cooler is designed to dissipate 18,000 B.Th.Us. per minute, and will reduce the oil temperature from 55 deg./60 deg. C. to 45 deg. C. when fed with cooling water at 27 deg. C. and handling 165 gallons of oil per minute.

Budenberg mercury-in-steel thermometers are fitted to all bearings and are connected through capillary tubing to indicating dials on the turbine gauge panel. Each thermometer has two contacts which can be adjusted independently and give an alarm if the bearing temperature reaches 68 deg. C., or operate the emergency trip circuit and shut down the set if the temperature rises to 80 deg. C.

BRAKING AND JACKING SYSTEM.

The braking and jacking equipment was supplied by Jones Tate & Co. Ltd., of Bradford, the system being shown diagrammatically in fig. 9. It comprises five rams, equally spaced and acting upon the brake ring which, as previously mentioned, is fabricated integrally with the lower ventilating fan on the magnet wheel. The top of each ram forms a flat plate which carries a heavy brake lining.

Although the braking system and the jacking system are interlinked, they are operated independently of each other. For braking, oil at 285 lb. per sq. in. from the turbine governor system passes through a reducing valve where its pressure is dropped to 50 lb. per sq. in. Between this valve and the ram cylinders is a solenoid-operated valve which

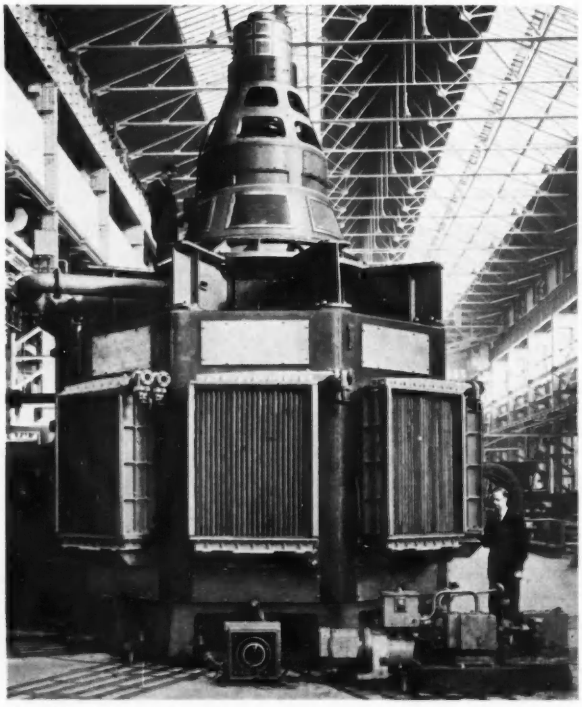


Fig. 10.—One of the alternators erected on the Works test bed.

opens automatically when the magnet wheel has slowed down to about half-speed. Oil is then admitted to operate the rams which apply the braking torque and bring the machine to rest.

By means of the jacking system the magnet wheel can be lifted when the machine is at rest to allow an unrestricted flow of oil through the thrust bearing prior to starting and also to enable essential maintenance work to be undertaken. For jacking, a far greater oil pressure is required and this is obtained from a Towler Bros. Electraulic high-speed multi-ram pump which delivers oil at a pressure of 1,650 lb. per sq. in. Mechanical stops limit the upward travel of the rams and are set to ensure that each ram rises to exactly the same height. A system of electrical interlocks ensures that the machine cannot be started up unless all the rams are in their fully lowered position. Oil from the rams returns to the jacking system through a high pressure, solenoid-operated release valve.

Hand-operated sustaining screws are provided for supporting the magnet wheel in the raised position. These screws are interlocked with the rams in such a manner that they cannot be operated until the magnet wheel is slightly raised so that incorrect operation is impossible. They also actuate the electrical interlocks associated with the rams and referred to in the paragraph above.

For both the braking and jacking systems the solenoid-operated valves are of the semi-balanced type and operate practically instantaneously. These valves are spring closed and are so arranged that the oil pressure assists closing, thereby ensuring that the valves seat tightly. The solenoids operate on a 125 volt D.C. supply and are continuously rated, economy resistances being provided to reduce automatically the consumption of the solenoid to about 10 per cent of full load immediately prior to the solenoid's reaching the end of its opening stroke.

TURBINE GAUGE PANEL.

The machine is operated from the turbine gauge panel on which are mounted all the controllers associated with the various oil pumps, braking and jacking systems, valves and so forth, temperature indicators and alarms for bearing oil, alternator windings and cooling air, as well as lamps to give a continuous indication of the operation of the complete plant.

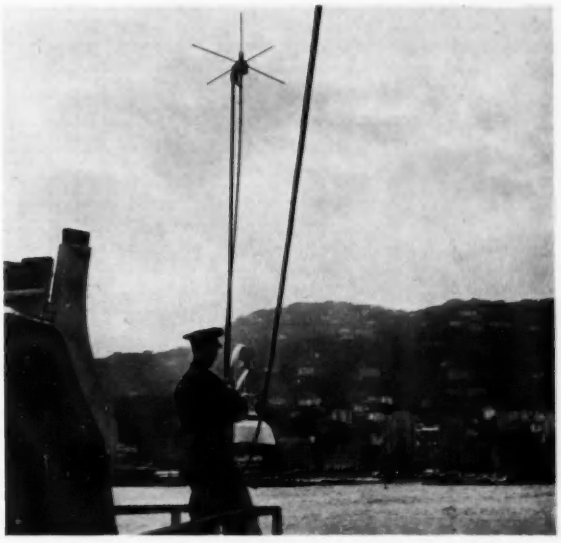
ACKNOWLEDGMENT.

The author wishes to acknowledge the help given by The Hydro-electric Commission of Tasmania in providing information on the development of hydro-electric power in Tasmania and for permission to publish this article and illustrations.

Ship-Shore Link at Hong Kong

A comprehensive V.H.F. system for harbour communication has been installed at Hong Kong. The equipment, manufactured by the G.E.C., provides direct communication between ships in harbour and subscribers on the main Hong Kong telephone exchange, and also between the ships themselves.

A portable V.H.F. transmitter/receiver is taken on board a ship as soon as it enters harbour. The vessel is thus, at once, incorporated in the V.H.F. network and connected to the main telephone exchange.



A Modern Thermal Pattern Relay for Motor Protection

(Part 2)*

By H. S. LEWIS, B.Sc., A.M.I.E.E.
Chamberlain & Hookham, Ltd.

CHARACTERISTIC CURVES OF TYPE H RELAY.

A detailed discussion regarding the correct application of thermal overload protection for induction motors is outside the scope of this article, but it is necessary to indicate one or two important considerations which affect the choice of the relay characteristic curve. At the instant of switching on a three-phase star or delta-connected motor there is an inrush of current equal to several times the normal full load current, which decreases as the motor accelerates to a near-synchronous speed, the final speed and current depending upon the mechanical load applied to the motor. The duration of this starting surge is not sufficient to damage the motor owing to its inherent thermal capacity, but prolonged overloading or single-phasing ultimately results in overheating and damage to the machine. A protective relay for such an application therefore must make full use of the machine thermal capacity to avoid tripping on starting current, but must not endanger the machine on sustained overloads. Ideally the characteristic of the relay should exactly match that of the motor, but as the characteristic of the machine depends not only on the manufacturer but on the frame size, type, etc., it would not be practicable to design a relay for individual motors and some compromise is necessary. The expected range of motor characteristics was examined and it was found that in general motors could be divided into two groups, those used for low-inertia drives and/or having a starting current of seven times full load or less, and those used for high-inertia drives and/or having a starting current exceeding seven times full load. The type H relay affords adequate protection for the first group, and the type HST relay, to be discussed later in this article, is suitable for the second group.

The type H relay gives protection against

* Part 1 appeared in Vol. XXI, No. 2, April, 1954.

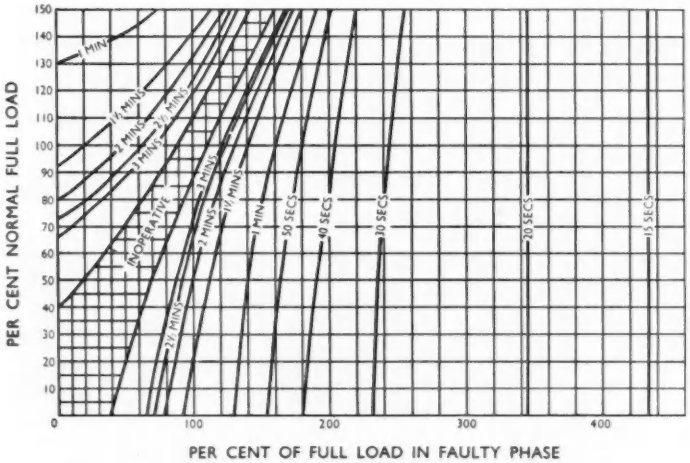


Fig. 17 (a).—Generalised characteristic curves for type H relay. Phase-unbalance.

overcurrent and phase unbalance, and for each of these there are so many combinations of circumstances that it is not possible to draw a comprehensive characteristic operating curve. It is possible, however, to represent the operation of the relay as shown in fig. 17(a) and 17(b), where points having equal operating times have been joined together to form lines from which the operating time for any set of circumstances may be estimated with reasonable accuracy. The setting of the relay for phase-unbalance protection is not adjustable, but depends on the initial separation of the two silver strips forming the H-shaped assembly described above. If the relationship between heater current and bimetal spiral deflection were linear, equal deflection increments would correspond to equal current increments which could be expressed as a constant percentage of the relay full-load current. This relationship is not linear, however, the deflection being approximately proportional to the 1·719th power of the current, and the current increments for constant deflection increments are varying percentages of the relay full-load current. Fig. 17(a) therefore shows lines of constant time for various combinations of currents in one healthy phase and the phase carrying fault current.

For overcurrent protection the relay setting is adjustable by hand, as described previously. If the relationship between heater current and bimetal spiral deflection were linear, and if the average rate of deflection of the spiral were directly proportional to the heater current, the relay operating time could be plotted against current expressed as a multiple of the setting current, and one time curve would suffice for all settings. These relationships are not linear, however, and fig. 17(b) therefore shows lines of constant time for various combinations of relay setting and applied overcurrent. Such a set of curves would be confusing if printed on the main label, and the practice adopted is to show the characteristic curve for one particular set of conditions. The main label of the type H relay includes the curves shown in fig. 18, which give the operating times of the relay when set to 125 per cent, the current being expressed in multiples of the relay full-load current. The characteristic of most interest is that showing the operating time of the relay from cold, called the " starting " curve, but an additional curve is given showing the operating time of the relay from a steady state of 100 per cent current, called the " running " curve. Again, many values of " running " current could be taken to obtain various " running " curves, but the one shown is sufficient to indicate the expected behaviour of the relay.

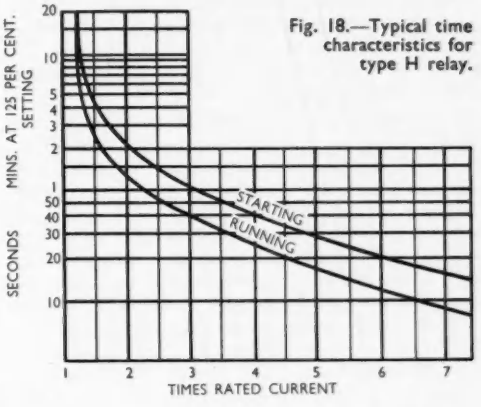


Fig. 18.—Typical time characteristics for type H relay.

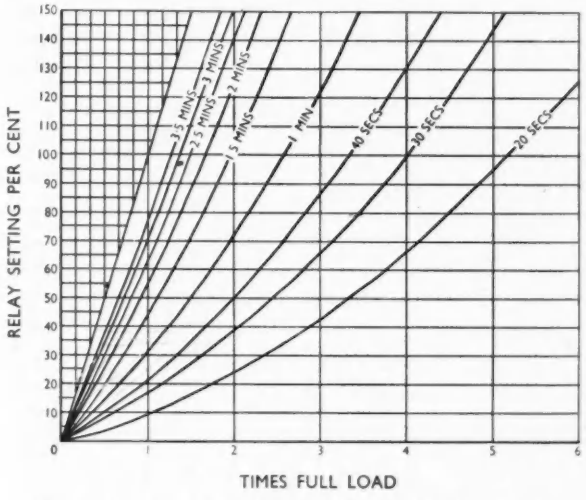


Fig. 17 (b).—Generalised characteristic curves for type H relay. Overcurrent (starting).

The adjusting screws attached to the heater are used so to position it with respect to the bimetal spiral that the steady deflection of the bimetal is correct at 125 per cent of rated current. The actual spacing between the heater and the end-face of the spiral differs in individual relays as a result of a

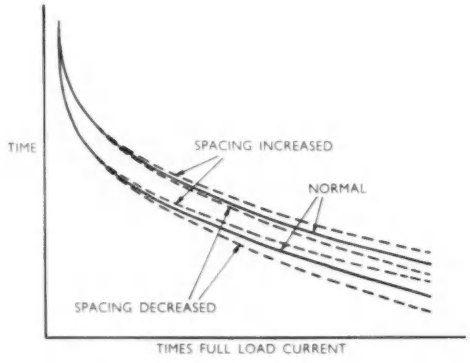
number of factors, some of which are mentioned below. In each case the resultant effect on the relay characteristic is shown in fig. 19(a). The spacing is increased when the abnormality is:

(*i*) High heater resistance due to over-slotting;
or (*ii*) High resistivity of heater material;
or (*iii*) Low heater material thickness;
or (*iv*) Low coefficient of thermal conductivity of the mica;
or (*v*) High bimetal deflection/temperature coefficient;

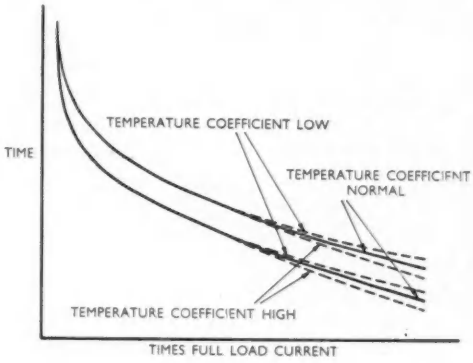
and the spacing is decreased when the abnormality is opposite to those mentioned. If a metal plate is inserted between the heater and the heat shield (a method not used in the type H relay because of possible instability) it would be expected to act as a reflector and raise the temperature of the heater above normal, but in fact it acts as a cooling fin, lowering the temperature of the heater and necessitating a decrease in the heater/bimetal spacing. In this case the relay is again speeded up because the cooling effect of the plate does not come fully into action within the operating time of the relay at the higher loads.

The deviations from the normal time curves caused by the abnormalities so far considered are produced indirectly and depend on the resultant common variable, namely the heater/spiral spacing, but other abnormalities can occur which affect the time curves directly. It is usually assumed that the nickel alloys used for the heater have negligible temperature coefficients of resistance, but in fact there is a change in resistance with variation in temperature, typical curves being shown in fig. 20. As the heater current is independent of changes in heater resistance the resultant temperature of the heater for a given current will depend upon the temperature coefficient, and the relay time curves will be affected in the manner shown in fig. 19(b). Variation in the thermal capacity of the spiral, the texture of the edges at which the heat is absorbed by the spiral and possible non-linearity of the bimetal deflection/temperature curve all affect the relay time curve directly, but are usually of such small magnitudes as to be negligible. A further factor affecting the time curve of the relay is one which has already been mentioned in the discussion on the construction of the heater, namely, the thermal capacity of the heater assembly. If any of the abnormalities mentioned above are present and tend to slow down the relay, the removal of one part of the lag plate provides an easy means of partial or total correction by reducing the thermal capacity of the heater assembly.

In the preceding discussion of temperature compensation by the inclusion of an unheated spiral, emphasis was laid on the desirability of avoiding zero drift due to changes in temperature, but in addition there remains the possibility that the time curve of the relay may be sensitive to temperature changes. Further consideration shows, however, that the operational deflection of the spirals depends on the temperature rise above ambient, due to the heater current, rather than the absolute temperature of the bimetal, and as long as the bimetal is operating on the linear portion of its deflection/temperature characteristic for the maximum range of ambient temperatures plus the working temperature rise, the time curves of the relay should be unaffected.



(a) EFFECT OF SPACING BETWEEN HEATER AND SPIRAL



(b) EFFECT OF TEMPERATURE COEFFICIENT OF RESISTANCE OF HEATER

Fig. 19.—Effect of various factors on the relay characteristic curve.

These conclusions are confirmed by the consistent time curves which have been obtained on the type H relay at widely differing ambient temperatures.

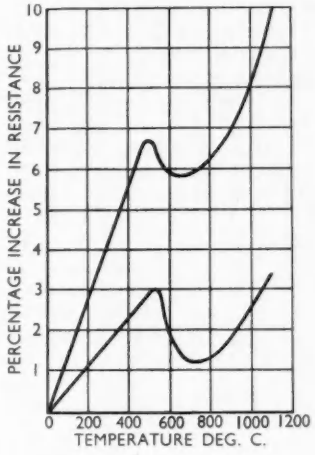


Fig. 20.—Variation of heater resistance with temperature.

A further characteristic which is of interest is the reopening time of the relay contacts after operation, as the motor cannot be restarted with the relay contacts closed. The contact reopening time is determined by the heat stored in the relay and this depends on a number of factors which include :

(*i*) The magnitude of the excess current ;
(*ii*) The duration of the excess current ;
(*iii*) Whether the excess current occurred under starting or running conditions ;
(*iv*) The relay setting.

Typical starting and running contact reopening times are shown in fig. 21, on the basis of excess current existing only for the operating time of the relay, set at 125 per cent.

THE INTERPOSING TRANSFORMER.

The type H relay is suitable for the protection of motors which have starting currents of up to seven times the normal full load, and which are used for low-inertia drives, but where protection is required for motors driving conveyors, crushers, etc., having high inertia, the relay must be capable of withstanding much higher starting currents while the motor is accelerating and it must also have longer operating times. In these circumstances it is usual to interpose a saturable transformer between each main current transformer and its associated heater so that beyond a certain primary current there is practically no increase in the current fed to the heater. Such an arrangement is used in the type HST relay which incorporates all the features of the type H relay together with one saturable transformer per phase, all contained in one case.

In order to obtain the required relay time curve the saturable transformer must be designed to give a known non-linear characteristic. The effects of winding arrangements, core material and air gaps on the input/output characteristics of a saturable transformer have been described in a previous article,[4] and a brief description of the transformer will suffice. The silicon-steel laminations are L-shaped and interleaved to form a hollow square, with both primary and secondary windings on one limb, and by measuring the input/output curve under loaded conditions the number of laminations and the size of the air gaps are adjusted to obtain the characteristic which, as found by experience, will produce the required time curve on the completed relay.

The rating of motors in horsepower and the use of various system voltages lead to odd

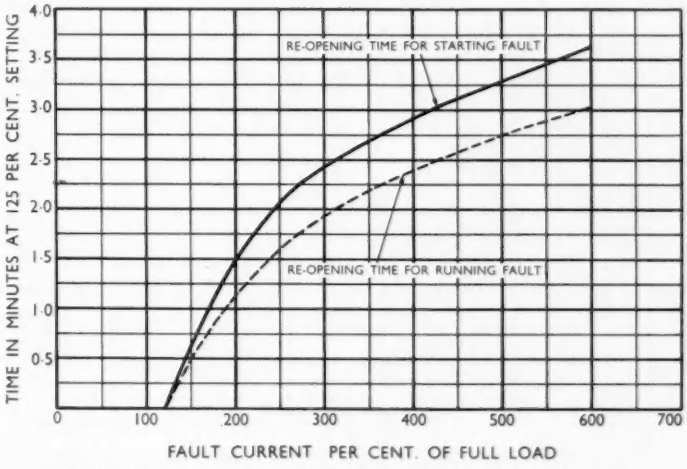


Fig. 21.—Typical overcurrent/contact-reopening-time characteristics for type H relay.

values of line current which correspond to full load on the motor, and it often happens that the nearest standard size of main current transformer is widely different from the required size, resulting in the anomaly of full load on the motor not corresponding to 100 per cent on the relay. This problem is eased by extending the interposing transformer primary winding to give relay ratings corresponding to 0·8 and 0·9 of its nominal rating and hence it is possible by selection of the appropriate tapping more nearly to match the 100 per cent setting of the relay with full load on the motor. The tappings are brought out to three channels of extruded section brass which form a three-position plug bridge. A common connection strip is supported over the channels, under spring tension, and the insertion of a heavily silver-plated connecting plug in any channel ensures connection between that channel and the spring-loaded connection strip. The plug may be removed and inserted easily by hand, and a safety contact connects in the highest tapping when the plug is withdrawn, thus ensuring that the main current transformer is not open-circuited. An associated label includes markings under each channel giving a clear indication of the effective relay rating in amperes, e.g. a 5-amp. relay has plug settings of 4·0, 4·5 and 5·0 amp. The plug bridge is mounted directly on to the transformer forming a complete sub-assembly, three of which are mounted below the thermal elements of the relay.

For some applications there is no necessity for main C.T.s to be fitted and the relay is connected

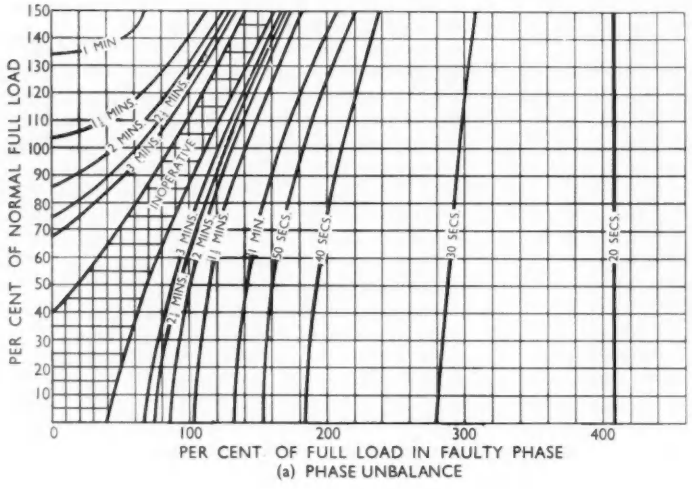
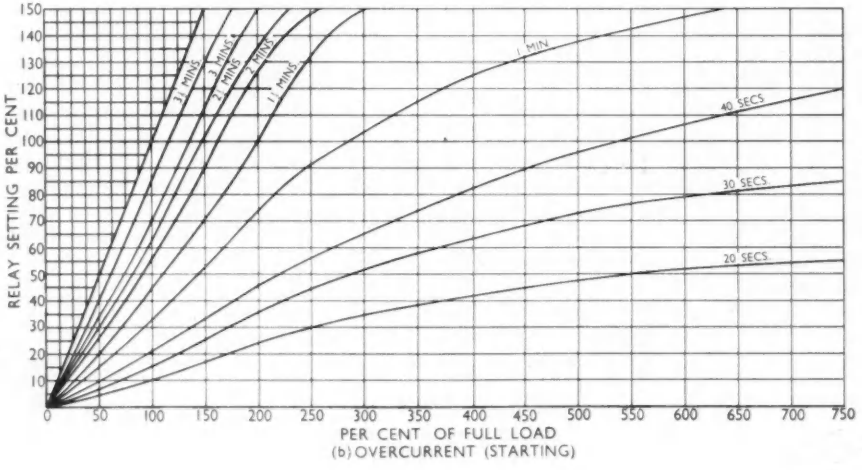


Fig. 22.—Generalised characteristic curves for type HST relay.



directly into the lines. In such cases the saturable transformer primary is wound for the correct line current and no tappings are required. The secondary output current of this transformer at full load is 1 amp. irrespective of the primary

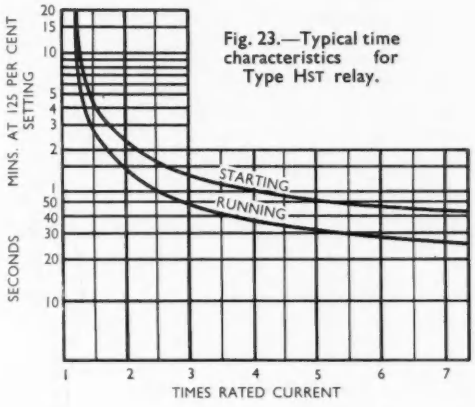


Fig. 23.—Typical time characteristics for Type HST relay.

winding rating or arrangement and by this means together with the savings already accomplished in heater consumption the burden of the type HST relay is only 4·0 VA per phase compared with 6·5 VA per phase for the conventional pattern relay with saturable transformers.

CHARACTERISTIC CURVES OF TYPE HST RELAY.

The type HST relay gives protection against overcurrent and phase unbalance for the group of motors having prolonged starting currents in excess of seven times normal load. Again it is not possible to draw a comprehensive characteristic curve but the operation of the relay is represented by fig. 22(a) and fig. 22(b) where points having equal operating times have been joined together to form lines from which the time for any set of circumstances may be estimated with reasonable accuracy. Comparison with fig. 17(a) and fig. 17(b), respectively, gives an indication of the modifying effect of the saturable transformer on the operating times. A more obvious comparison can be made between fig. 18 and fig. 23 which shows the starting and running curves of the relay when set to 125 per cent. These curves are printed on the main label of the type HST relay.

The operating curves of the type HST relay are affected by the same factors which affect the operating curves of the type H relay, but in addition variations in the calibration of the interposing transformer must be taken into account. Over the range of currents covered by the scale, i.e. 0-150 per cent the transformer input/output curve is reasonably linear and the same scale calibration suffices. Changes in the ratio of the transformer within this range affect the heater/bimetal spacing with the results previously discussed, and summarised in fig. 24(a). Beyond this range the characteristic is non-linear and the effect of the transformer calibration in this second zone is summarised in fig. 24(b).

A further possible cause of variation in the type HST relay time curve is the presence of harmonics in the current waveform. As discussed in detail in the previous article,[4] the " instantaneous impedance " of a saturable relay varies during each current cycle, attaining a maximum at those parts of the cycle in which the core of the transformer passes from saturation in one direction to saturation in the other. If a sinusoidal voltage is applied to such a relay for testing purposes the current is non-sinusoidal, suffering a depression at those parts of the cycle in which the impedance is a maximum, and the relay time curve is slowed down. The usual

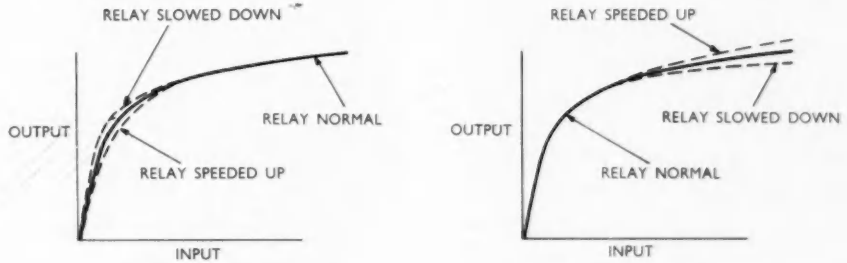


Fig. 24.—Variations in transformer calibration and the effects on relay time curves.

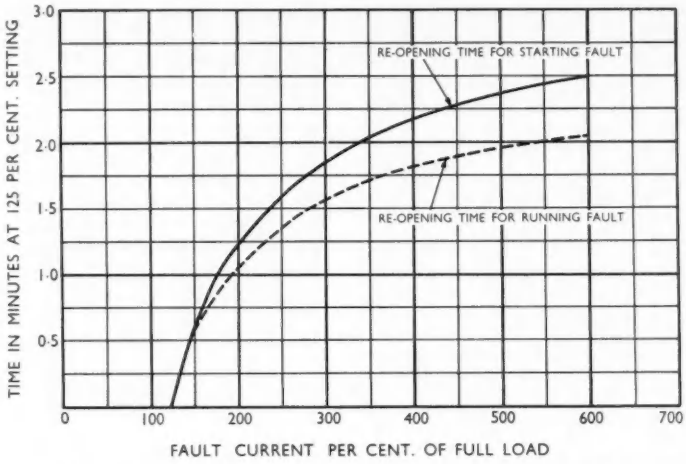


Fig. 25.—Typical overcurrent/contact-reopening-time characteristics for type HST relay.

practice, therefore, is to connect in series a linear impedance exceeding four times the unsaturated impedance of the relay so that changes in the "instantaneous impedance" of the relay are small compared with the total impedance of the circuit, wherefore the current waveform is very nearly sinusoidal and the normal time curve is obtained.

In a protective scheme where the relay is fed from main current transformers having insufficient capacity the waveform of resultant current fed to the relay again suffers local depression with resultant slowing down of the relay time curve. In this respect the lower full-load burden of the type HST relay (4·0 VA) compared with the conventional relay (6·5 VA) offers a distinct advantage in the reduction of main current transformer design problems. Alternatively, inferior main C.T.s give better performance with the type HST relay than with the conventional relay.

The cause of current waveform distortion in the two cases mentioned above is the varying "instantaneous impedance" of the relay, and in general it may be stated that if the distortion of the current waveform can be directly attributed to this source, the relay will be slowed down. In other cases of distorted current waveform the performance of the relay will depend on whether the waveform suffers a depression or a peak at those parts of the cycle where the relay has maximum impedance.

Typical starting and running contact reopening times for the type HST relay are shown in fig. 25 on the basis of excess current existing only for the operating time of the relay, set at 125 per cent.

FURTHER EXTENSIONS TO THE RANGE OF MOTOR PROTECTION RELAYS.

The main subject of this article is the new thermal protection relay previously discussed, but there are other motor protection relays which incorporate this unit and which will be described briefly before concluding.

In those applications where short-circuit

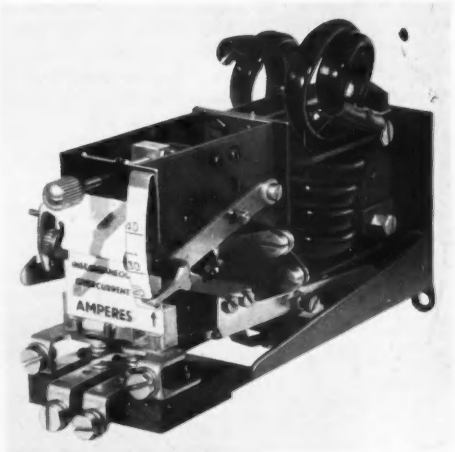


Fig. 26.—Instantaneous overcurrent relay element type AM.

faults result in excessive currents, the equipment may suffer appreciable damage during the inherent time lag of the thermal relay, and it is necessary to include a device which will ensure immediate disconnection of the supply. Rapid disconnection can be accomplished in some cases by the use of suitably rated H.R.C. fuses, but a more convenient method is the connection of an instantaneous overcurrent relay in series with each phase of the thermal unit. With this in mind, the instantaneous relay type AM has been developed which, when incorporated in the same case as the thermal unit, gives complete motor protection. The two additional types of relay available are the type H/AM and type HST/AM, the oblique stroke indicating the combination of the respective units in a common case. Both of these relays include three instantaneous units which can be arranged to give overcurrent protection in all three phases or overcurrent protection in two phases and earth-fault protection. The usual settings of the instantaneous overcurrent elements for the relays type H/AM and type HST/AM are 4-8 times full load and 8-16 times full load respectively, and in each case the added burden at normal full load due to the instantaneous elements is negligible. For earth-fault protection the usual settings are 0·2 - 0·4 times full load.

The type AM relay is designed on conventional lines but incorporates novel features. An energising coil is wound on an inverted U-shaped magnetic circuit the open end of which attracts a laminated armature. The armature is attached to one end of a pivoted beam and at the other end are mounted two moving contacts which are connected via flexible ligaments to two terminals, the ligaments being designed to have minimum restraint on the motion of the beam. Enclosing the moving contacts are two sets of fixed contacts which can be connected to give :

(*i*) 2 normally open contacts ;
or (*ii*) 2 normally closed contacts ;
or (*iii*) 1 normally open contact and 1 normally closed contact.

All connections are accessible from the front.

The pivoted beam is normally restrained in the unoperated position by a return spring, the tension of which is adjustable by means of the small knob protruding from the front of the element. The adjustable end of the return spring is connected to an indicating pointer which is associated with a scale calibrated in amperes and clearly visible on the front of the element in fig. 26. A novel tripping indicator is also actuated when the relay operates, the motion of the beam unlatching a hinged flap which rotates through 180° about one edge. In the unoperated position the visible surfaces of the flap and target are both painted black, but in the operated position the flap covers the black portion of the target and exposes the remainder

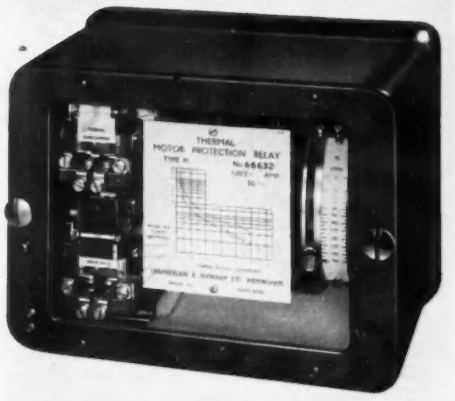


Fig. 27.—Type H relay with tripping indicators/contactors in projecting pattern case.

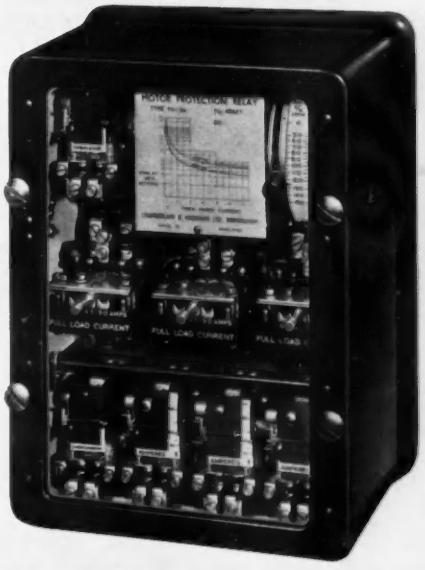


Fig. 28.—Type HST/AM relay, with tripping indicators/contactors in projecting pattern case.

of the target and its own reverse face. These surfaces are painted white with a red diagonal stripe. Thus the actual change in indication area is twice that of the flap. If required an additional pin may be attached to the flap which locks the contacts in the operated position, rendering them hand-reset; otherwise the contacts are self-resetting, i.e. they reset on the cessation of operating current. In all cases the tripping indicator is manually reset. Care is taken to statically balance each pivoted beam so that external vibration will not operate the relay,

Fig. 29.—Type H relay in projecting pattern case.

a distinct improvement over the conventional pattern relay.

A further extension to the above relays is afforded by the inclusion of indicators which show whether a fault cleared by the thermal unit was overcurrent or phase-unbalance. An inherent feature of any thermal relay which gives combined overcurrent and phase-unbalance protection is the interdependence of the contacts corresponding to those two fault conditions. The operation of the overcurrent contact arrests the motion of the balance contact associated with that phase; the remaining contacts continue to move under balanced overcurrent conditions and give a false indication of phase unbalance. Such a condition cannot be analysed readily by later observation of the relay as the same condition may occur with phase unbalance severe enough to close the overcurrent contact. The only satisfactory method of determining the original fault is by the inclusion of two electrically operated indicators so interlocked that only one can operate, the circuit to the other one being automatically opened by a contact on the first. This arrangement is available on types H, H/AM, HST and HST/AM relays, the electrical indicators being based on the overcurrent relay type AM previously described. The adjusting knob and scale are omitted and the

Fig. 30.—Type HST/AM relay, with tripping indicators/contactors in flush pattern case.

coil is wound for the required value of tripping current or voltage. An advantage of using the same basic element is that apart from the interlocking contacts, additional contacts for reinforcement, or normally closed contacts, or double circuit contacts can be fitted for alarm circuits, etc., thus the indicator combines with it the functions of an auxiliary contactor. A type H relay with indicators/contactors is shown in fig. 27, and a type HST/AM relay with indicators/contactors is shown in fig. 28, the indicators/contactors being on the left-hand side in both photographs.

CASES.

Motor protection relays in the type H series are available in three sizes of cast aluminium case, which may be termed small, medium and large. The small case is for the type H relay without indicators/contactors as shown in fig. 29, and the medium case is for the type H relay with indicators/contactors as shown in fig. 27. Relays

type H/AM, HST and HST/AM with or without indicators/contactors are fitted in the large case, a typical arrangement being shown in fig. 28. In addition to the projecting patterns shown, each size of case is available in a flush pattern.

The bases on which the relays are mounted are common to both flush and projecting patterns and are so arranged that when used for the projecting pattern the four corners alone touch the panel, thus avoiding a ledge on which dust, etc., could accumulate.

The projecting pattern covers are based on the same lines as existing Chamberlain & Hookham relay cases which are notable for their smooth streamlined appearance. The only protrusions occur on the front face and consist of the slotted cover fixing nuts and a single resetting button which is arranged to reset all the instantaneous elements and indicators/contactors simultaneously.

The flush pattern covers consist of two separate parts, the first of which is an open-ended box which screws to the base in place of the projecting pattern cover. Around the outer edge of the box is a flange having raised bosses which are placed in contact with the front face of the panel. In positions corresponding to the raised bosses, detachable clamps are fitted to the box, so that the panel is gripped between the clamp and raised boss. The second part of the flush cover is detachable and carries the window, resetting button and fixing screws which engage with the flange of the box. A typical example of a flush pattern case is shown in fig. 30.

CONCLUSION.

By close attention to design details the VA burdens of the type H series of motor protection relays have been reduced to approximately 60 per cent of the corresponding conventional pattern relays, thereby relieving current transformer design problems. Relays are now available which give clear indication of overcurrent or phase-unbalance faults. These are important advances in the field of motor protection relays.

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Battery Locomotives

The illustration shows one of a number of battery locomotives, for which the G.E.C. has supplied the electrical equipment, in service on the underground railway system of London Transport Executive.

These locomotives, which operate from batteries and are independent of line supply, are essential for track renewal and general maintenance work during the night hours when passenger services have ceased and power has been switched off. They can also operate from the normal track supply whenever the section is alive.

Pilot Production: The Link between Research and Manufacture

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G.E.C. Research Laboratories.

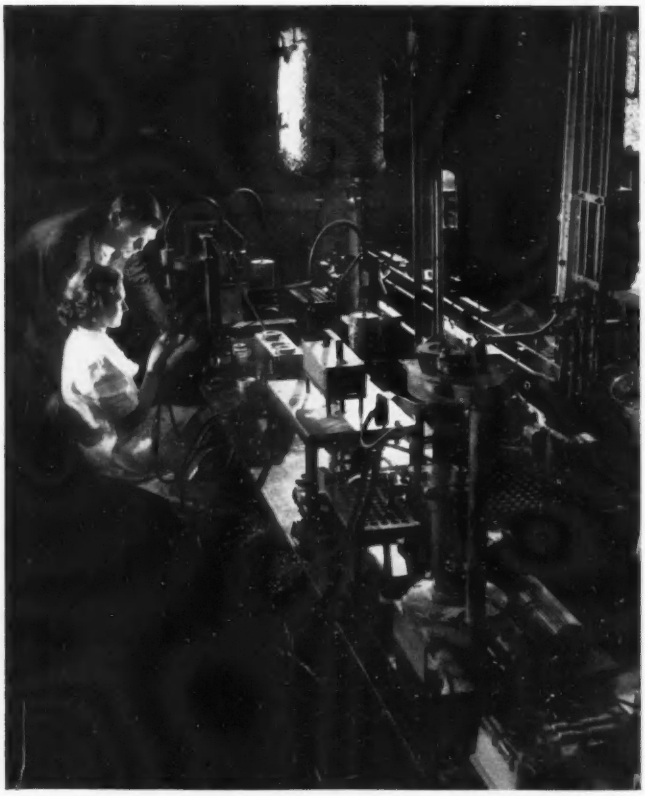


Fig. 1.—Part of the plan-working section of the Valve Try-out Unit; sealing-in on a new diode is being carried out.

Research laboratories are not normally associated with production. But it is nowadays agreed that some form of "try-out" production is necessary before a factory is committed to full-scale manufacture of a new product.

Although the term "try-out" is applied to any type of preliminary production, the range of such activity is very broad. At one end there is the elaboration of a new process; at the other, the development of a saleable article. The former is usually classed as "pilot" production and the outstanding example of this was the units set up during the war at Wembley to produce special valves quickly for the fighting services.

IT is a matter of experience that production of some sort is nearly always being carried out in the Research Laboratories, in spite of the fact that, as a general principle, everyone agrees that manufacture for its own sake is no part of their proper function. This activity is invariably one of a number of forms of "try-out" production which act as necessary preliminaries to full-scale manufacture, and the need for which common prudence dictates before a factory is deeply committed to a manufacturing programme based on a new development. Try-out production is frequently carried out in a factory; it often appears in the Laboratory, however, when there is something essentially new in a product or process on its way to the production line.

There is a vast range of types of development. At one extreme there is a new process. We may, for example, find it necessary to produce an

intricate new technique, perhaps for putting a fluorescent screen on a cathode ray tube. At the other extreme it may be necessary to develop a saleable article, perhaps a domestic appliance, where no new process is involved but merely new design, dimensions and assembly methods. For clarity it is perhaps desirable to use the term " preproduction " for the latter, reserving the expression " pilot " production for the case where a new process plays an essential part in the products, and employing the term " try-out " generically for any type of production preliminary to full-scale manufacture.

Usually, the preproduction, as well as much of the development of an article not involving new processing, is undertaken by the factory. Whenever this is possible it is desirable, since the factory ultimately has to take responsibility for production, and the more complete the part it plays at all stages of any development the better. The Research Laboratories are involved only when a technique or process is concerned which is new to the factory in question. It is the " try-out " stages of such developments which are so often found in the Laboratories.

Try-out production fulfils two needs, although they are not always clear-cut, and are frequently combined to a greater or lesser degree. The first is to provide assurance that a product can really be made satisfactorily under production conditions. This is particularly necessary when a new process is involved, and is the primary object of a pilot production plant. The second is to ensure that the best and cheapest production methods are found. This is always a main objective of factory preproduction. Perhaps the best examples of preproduction units employed for the latter purpose are those in constant use in some of the American companies. There this form of activity is taken so seriously as a means of improving engineering and production techniques and is carried out on such a scale, that the output of a preproduction unit is frequently comparable with the whole output of a factory in this country. It is, however, mainly with the former that this article is concerned, where the development of new processes or of articles employing new processes requires pilot production before they are finally accepted by the factory.

An examination of exactly why pilot production is necessary and how it can best assist industry requires a careful study of the relation between Research, Development and Factory Production. In making such an examination it is necessary to accept the fact that attempts to act according to a basic philosophy often fall short of complete success. To try to force a purely theoretical approach to any problem in defiance of circumstances, however, is as unprofitable as acting without any guiding principles at all.

Research may have many objectives ranging from the speculative accumulation of knowledge in the purely academic field to finding the means for solving a particular problem of immediate practical importance.

Development, however, has one aim only: to produce a product or article which can be manufactured reliably and economically. It is this singleness of objective which makes it both desirable and possible that development should be approached with a different mental outlook from that required in the various research activities.

Preferably there should be no element of research in a development. It is never possible

Fig. 2.—Assembly of cathode-ray tube systems as one stage in preproduction.

in any research to indicate with certainty when, or even if, success will be achieved. It is therefore impossible to draw up a time-table. On the other hand, if production and marketing dates are to be met, it is an essential part of really efficient development that such a time-table should exist and should be adhered to rigidly. This obviously becomes impossible if it is necessary during the course of a development to undertake as a side issue certain researches the success of which, in spite of being uncertain, is essential to the progress of the development.

The man on the Research Laboratories staff in charge of a new development of any type whatever, will usually find himself regarding it as being in two fairly distinct phases. The first comprises his need to assure himself that the new process—or product embodying the new process—is scientifically and technically sound. The second is the fulfilment of his responsibility to ensure that, in addition to being completely satisfactory in the Laboratories, it will also be satisfactory when the factory takes over. It must not be then discovered, for example, that unexpected new requirements have to be met to satisfy conditions essential for economic production ; for it might be found that these unexpected requirements produce a set of problems difficult or perhaps impossible of solution. In this event all the factory preparations are wasted with all that they usually involve in heavy expenditure. If such costly failures are to be avoided, any " unforeseen " difficulty must be foreseen before the factory incorporates the development in its manufacturing programme.

There is no standard method of handling these two phases. The particular means employed will depend upon the nature of the development, and to some extent also on the manner in which the research staff man responsible wishes to carry out his task. The first phase, however, will always require, in one way or another, careful study of the process, or of the products on which the process is used, by scientists and technicians in his laboratory. It is in this study that it is important that there should be no purely research element. At the final stages of this phase, which involves basically the assembly of existing knowledge and techniques to the solutions of the problems inherent in the development, the people carrying out the work will find themselves repeating their processes many times and often making a relatively large number of articles on which the new processes are employed—still under purely laboratory conditions. They will then say that their processess are satisfactory technically and scientifically if, under these very favourable conditions, they can always achieve the desired result, and, better still, are able to predict when divergences from the required result are likely to occur.

Fig. 3.—Piercing the drawing zone of a diamond wire-drawing die by the electric sparking method.

The senior man responsible is now, however, faced with the second phase of his task, for experience has shown that a successful completion of the first phase is no guarantee that a product embodying the new techniques can be made a successful item of merchandise, nor that the processes can be used with the necessarily rigorous requirements of foolproofness and economy essential in a factory. His difficulty is that his normal laboratory experimental techniques will probably differ in what may be important respects from those fit for routine

factory production. He will, moreover, usually be left with a very limited time in which to complete the final phase, if his date commitments are to be met.

How is this gap between the laboratory processes—now proved satisfactory as such—and the mass production stage to be bridged? The obvious way is to set up a small-scale production to find by trial if the necessary conditions are satisfied, and it is to a unit for this purpose that we have given the term " pilot " production. It is then possible to carry out regular day-by-day production trials, and this routine process is capable of yielding to the scientists and technicians valuable information which would hardly be obtained by laboratory experiment. The form which this new information takes will vary according to each particular development. It can, however, generally be classified under two main heads.

The first is that obtained from statistical data. Although the numbers involved may be rather small, the accumulation of records relating to various stages of the production and subjected to careful analysis by scientists who are specialists in their subject can often expose weaknesses in technique which—fairly easily corrected at this stage—might later involve a factory in heavy financial loss. This statistical procedure could frequently be carried out in the early stages of production in the factory, and in any event it should be continued, in a modified form, as part of process control when full production is attained. The virtue of having it initially under laboratory control, however, is that the experimental people who are responsible for the development can themselves watch the process under semi-routine conditions. They can then arrange to have it modified as the result of statistical analysis, and in the light of their own knowledge of the fundamental essentials on which the development has been built. So, by a process of enlightened observation on numbers large compared with those characteristic of an experimental laboratory but small compared with normal production standards, the new product can be guided through many of the pitfalls which might otherwise await it in the factory.

The second broad classification of the information which may be obtained at this stage of a development is that which permits the removal of what may almost be called a psychological difficulty in the scientists themselves. A research worker will often—especially if he has nurtured a development or some particular aspect of a development from its beginnings—exhibit a degree of skill and an inherent understanding of the processes, which he himself probably does not realise he possesses, and which are unlikely to be found in those later charged with organising and controlling factory production. For this reason it may be desirable to see whether he can provide complete written technical instructions entirely divorced from his own specialised skill. He frequently finds that he cannot, and—at least in the early stages of his career—will be somewhat bewildered by the fact and inclined to blame the man trying to carry out the production for some peculiar form of obtuseness. The inadequacy of his " conscious " knowledge could be found by losses in the factory, but it can equally well be found in small-scale production under his own eye. Having been convinced that, although he himself can produce a satisfactory result, he cannot tell anyone else how to do so,

Fig. 4.—Checking and recording the electrical characteristics of a disc-seal triode in the Valve Try-out Unit.

he must then find ways of bringing to the surface his own " know-how." He will watch the production process at each stage to find where failure occurs, and he will study his own directions in relation to the particular parts of the process concerned to see whether these have been misunderstood or are really inadequate. He may thus expose some gaps in his directions which he will then see how to repair. The task varies in the length of time it takes and in the difficulty of achieving complete success. It never fails to be very illuminating. It is usually found by experience that the written word throws a spotlight on vagueness and omission which is both embarrassing and valuable.

Fig. 5.—Glass-lathe in use as part of cathode-ray tube preproduction.

The research man will learn early in his career the value of this form of activity in warning him of possible technical shortcomings in a product for which he is responsible, and thus saving him the anxiety and frustration of seeing the failure of his work. Both he and the factory will often benefit also by improved understanding of each other's difficulties and point of view. There is less chance of the factory staff, on the one hand, feeling that they are handed incomplete developments, and of the research staff, on the other, of feeling that poor use is made of their work.

There are no simple and general answers to the questions : " How should such pilot production be organised ? " and " What relation should laboratory pilot production bear to factory production ? " Every new development requires careful thought in the light of all the existing circumstances. There are probably only three guiding principles : the production should be as small as is consistent with the requirements of the experimental people ; it should be as close as possible to the conditions of factory production and should have the benefit of the advice of the factory staff ; and, ideally, it should have a control independent both of the experimental people responsible for the development and of the factory production department.

The first thing to decide is whether it should be carried out in the factory or in the Research Laboratories. Although, if it is to serve its purpose, it must be laboratory production in the sense that it is necessary for the control to be in the hands of the research staff, it is not essential for it always to be carried out in the laboratory buildings. Indeed, it may often be desirable to have it in the factory when, for example, use of factory plant would be an advantage. On the other hand, it is not always practicable to ensure in the factory the complete freedom of action required by the research staff responsible for the work. Of course, the factory may, in addition or at a later stage, require preproduction under its own control, and on a much larger scale than would be attempted by the development people.

The size of the unit should be no larger than is necessary to ensure the regular flow of the product in question and to yield the experience and statistical information required. Usually it is found desirable for each type of product to have its own unit. Sometimes, however, where there are a number of products of which the basic techniques are similar, for example U.H.F. receiving valves, transmitting valves and magnetrons, it proves possible, with an obvious economy in staff and equipment, to have them all together.

The size and degree of isolation of the unit is not of such vital importance to its success as is a clear understanding of their responsibilities on the part of the man charged with the development and the man running the pilot production. The former will realise that his responsibility is to find solutions to the problems discovered during the pilot production, the latter to ensure that he really does unearth all the difficulties likely to be found later in the factory.

In this matter of try-out production, as in all others, the limited resources available often result in the actuality falling short of the theoretically ideal arrangement. It has been known to happen, for example, that the man completely responsible for the development has also become completely responsible for the pilot production. This is, ideally, wrong, and the results, although valuable, almost certainly less so than they should be. It has been known also for pilot production to be mixed up in some degree either with experimental development or with factory production, with consequences not happy for either.

Fig. 6.—An early stage in the preproduction of diamond wire-drawing dies: measuring the angle of the steel-piercing needle.

Perhaps the outstanding examples of pilot production—at least as far as our own Company is concerned—were the Research Laboratory units which were set up during the war to produce special valves and other devices for the fighting services. Such units were by no means a new conception in the Laboratories. It is a curious fact, however, that the development of their use and of an improved understanding of the best means of operating them received powerful new impetus for a reason that had little to do with the real functions of a try-out unit: the imperative need in the circumstances to produce valves quickly for operational use even if only in limited numbers.

Prior to 1939, U.H.F. valve development had gone on with increasing intensity, and development had far outstripped the ability of the factory to produce such devices, or even of the technical people to give the factories sufficient guidance to enable them to contemplate production. Nevertheless, the valves were required in relatively large numbers with great urgency. The try-out unit was found to be the answer. The organisation, which evolved quite quickly, consisted in having in charge of each unit an experienced scientist who was completely autonomous so far as his production was concerned, but who remained closely in touch with the section which had developed the valve and took his production data from them. He was in all cases a technician of sufficient experience and ability to be able to interpret the information he was given and—more important—to be aggressively conscious of the fact when his information was inadequate.

As each new design of valve reached a stage at which it was functionally useful, operational equipment could be safely designed round it; and the services had the guarantee that at least limited supplies of valves would be forthcoming from small-scale production units operated very closely in conjunction with the scientists who had been responsible for their development and design. This procedure was completely successful; the Services had the valves when they needed them, in some cases perhaps years before a factory organisation could have been evolved to deal with them. At the same time the factory organisation was enabled to expand its output

on the more standard types, and to take over, without the risk of severe dislocation, the newer types as they became more clearly understood by their designers as a result of production experience. At one time during the war the Laboratories had more than ten separate units engaged in the try-out production of these special devices.

There are many other examples of Laboratory production. Special cathode ray tubes were produced during the war for reasons and in circumstances similar to those obtaining for the special valves. Like the valve pilot production, this was continued after the war at the Laboratories, and, their processing becoming well understood, one type after another has since been transferred to the factory organisation. The history of crystal valves followed, and is continuing to follow, an almost exact parallel.

Again during the war, the loss of the traditional sources of diamond dies for wire drawing placed the whole of the lamp and electronics industry in jeopardy. The Laboratories quickly developed methods of making these dies, but there was no factory at that time able to take over the production. It was set up, therefore, at the Laboratories, with the incidental advantage that the processes could be studied for a long time under pilot plant conditions, and it is only in the last year or so that the Lamp Works has taken over the production. Boiling plates, heating elements, Heavy Alloy, sapphires, piezo-electric crystals and special wires are other examples of non-electronic products which have been produced in the Laboratories before transfer to a factory, and the list could be further extended.

It is obvious that in circumstances of normal peace-time commercial activity the economics of try-out production are of paramount importance. They require careful examination for each individual case. In making the survey it should be remembered that, looked upon as part of the experimental development, try-out production is always very costly, since to set up an independent unit usually requires at least some new plant, and the training—or, at any rate, adaptation—of staff. Moreover, once set up, to achieve anything like the maximum possible results, it will probably be operating for many months and may even continue after production has been established in the factory. It is for these reasons that the unit should be small. To offset this, however, it is to be remembered that its purpose is to reduce the factory teething troubles which may easily prove vastly more costly than anything that try-out production could absorb, and which are often accepted as an inevitable part of the introduction of anything new. Sometimes the cost of a try-out unit can be partially recovered by the sale of its own products which, although uneconomic to produce, are often perfectly acceptable for the market. The American preproduction factories already mentioned would cost a quite impractical amount to operate were it not that they are able to recover a large part of their expenses by the sale of the output.

In all the examples so far mentioned, the main reason for initiating production in the Laboratories was the need to develop the manufacturing technique under the eyes of the men responsible for the development. Other important considerations may enter, however, in varying degrees in each instance, besides the purely technical problem of getting a new development launched satisfactorily in the factory. One is sometimes faced with the dilemma, for example, of not being able to find whether a worthwhile market exists for a new product without actually trying it out over a relatively long period. Yet no factory is prepared to undertake full-scale production until there is assurance of a reasonably large and continuous output. In these circumstances the only solution seems to be small quantity production—which may in itself be uneconomic—carried out over any period necessary to allow the commercial possibilities to be fully tried out. In this way, one may hope to avoid losses which might otherwise be incurred through entering prematurely a market that had not been properly explored. Even if a factory could be found willing to undertake small-scale production in these circumstances, it is often economically justifiable for production to be carried out at the Laboratories when the adaptation of staff and equipment to the pilot production of a new product is more easily contrived than in a factory with its less varied facilities.

It is certain that preproduction is an essential tool in industry. It is equally certain that, although we have learned much concerning its use, we have not yet fully exploited its economic and technical possibilities. It is probable that as a subject it has not received the complete study that its importance deserves, and this examination must be continued if the Company is to make the fullest use of its resources.

Manchester-Glossop Railway Electrification

By E. H. CROFT, A.M.I.C.E., M.I.E.E.
Traction Consultant.

Fig. 1.—Six-car train in Glossop Station.

INTRODUCTION.

PRIOR to the second World War, work had been started on the electrification of the Manchester-Sheffield section of the then London & North Eastern Railway. This was not only to serve the very heavy passenger and freight service between Manchester and Sheffield via the Woodhead tunnel, but also included a section of suburban electrification around Manchester. The electrification was planned to cover Manchester (London Road) to Hadfield and Glossop, a distance of approximately 13 miles, with a loop from Gorton to connect with the Central Station at Manchester, a distance of approximately 9½ miles, and serving a further suburban area.

The G.E.C. received the order for the complete electrical equipment for the suburban rolling-stock, consisting of 8 train units, each unit comprising one motor coach, one trailer coach and one driving trailer. Fig. 1 shows such a unit in service.

After the outbreak of war, work was suspended and did not start again until late in 1948, and for the time being the loop from Gorton to Central Station was to remain in abeyance. The route now electrified and opened to regular service is seen in fig. 2, the loop to Central Station being shown dotted.

ROLLING-STOCK.

As mentioned, the train unit consists of three coaches, a driving motor coach, a trailer, and driving trailer coach. Thus the smallest train consists of three coaches, and trains of six

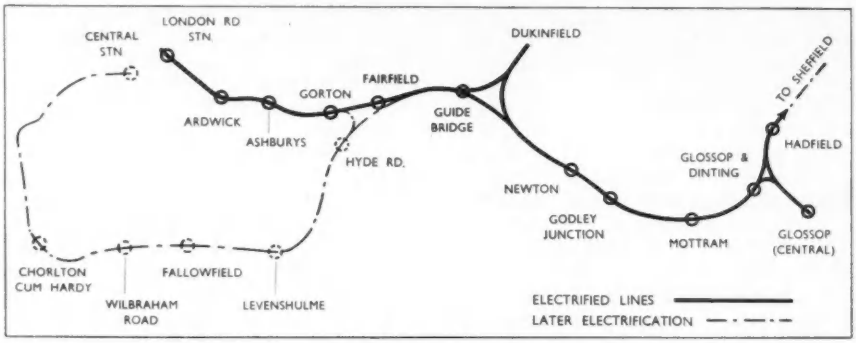


Fig. 2.—Map of the electrified line.

coaches may be formed by multiple unit operation of two train units.

Each motor coach has one driving position, a guard's and luggage compartment and seating for 52 third class passengers. The trailer coaches each seat 64, a number being first class passengers ; the driving trailer has one driving position and seats 60 third class passengers. In addition, each train unit can carry 232 standing passengers for rush-hour conditions.

The motor and trailer coaches were supplied by the Metropolitan-Cammell Carriage and Wagon Co., Ltd., and the driving trailer coaches by the Birmingham Railway Carriage and Wagon Co., Ltd.

The three types of coach are of all-steel construction, having an open type saloon body with both transverse and longitudinal seats. On each side of each coach two 4 ft. 6 in. sliding doors are provided, with ample adjacent floor

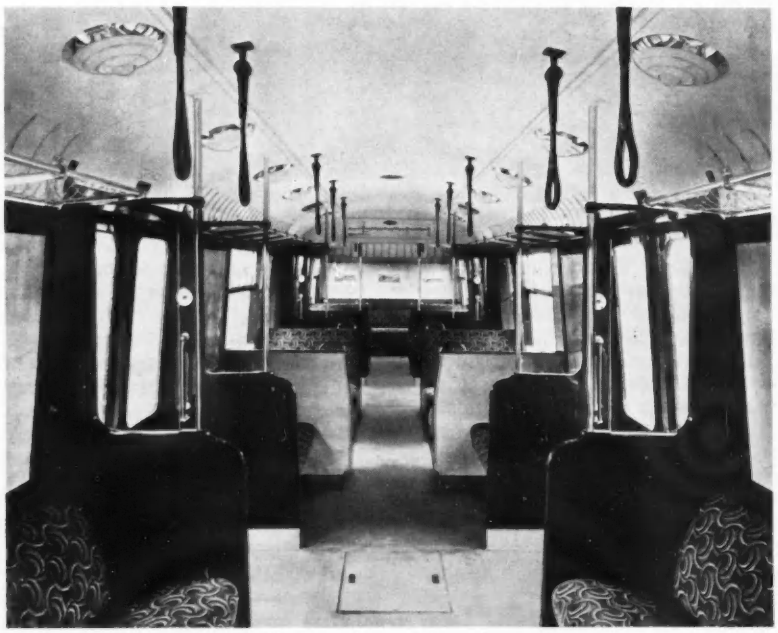


Fig. 3.—Interior of one of the motor coaches.

space for standing passengers. The doors are provided with electro-pneumatic control, so that they may be controlled throughout the train by the guard. The brakes are of the Westinghouse air type and are electro-pneumatically controlled. Bogies are of the usual swing bolster type.

In accordance with modern practice, all power and control equipment, other than the essential master control apparatus situated in the driver's cabs and in the guard's compartments, and the pantograph collector equipment situated on the roof, is mounted below floor level to provide the maximum seating and standing capacity. The interior of a motor coach is shown in fig. 3.

Table 1 gives the leading data of each type of coach, while Table 2 gives their required approximate performance. It should be realised that the route includes gradients above the average and operates in country of a hilly, or almost mountainous, character. For example, from Manchester to Hadfield the average up gradient is 1 in 180, and over five miles are 1 in 133 or steeper, the maximum being 1 in 77.

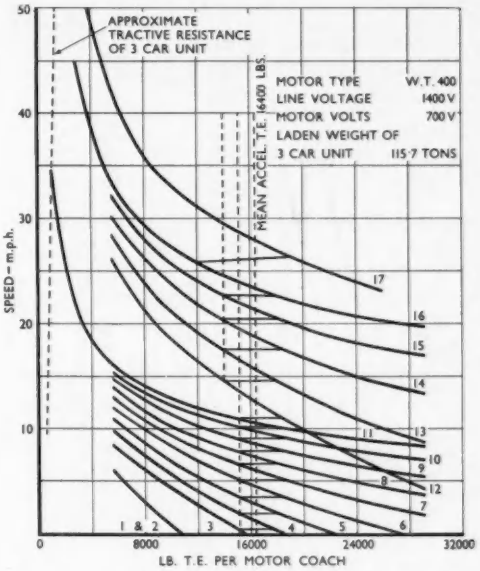


Fig. 5.—Performance curves.

MAIN POWER SCHEME.

Power is supplied from an overhead conductor at a nominal voltage of 1,500 D.C. But, since the stock will operate on lines where heavy freight locomotives regenerate, the equipment is designed to function satisfactorily up to 1,800 volts. The average voltage is 1,400, and the minimum voltage 1,000; the equipment will, however, operate satisfactorily on a voltage as low as 750. It will therefore be realised that, from the point of view of the country over which the stock will run and the line voltage range to be met, the service may be regarded as severe in comparison with that of many suburban lines.

Each train unit is powered by four motors having an hourly rating of 185 h.p. at 700 volts full field and 210 h.p. at 700 volts weak field. The motors are of the axle hung type, one mounted on each axle of the motor coach.

Fig. 4 shows the power circuits in schematic form. Current is collected by a single pantograph and feeds the power circuits through a roof

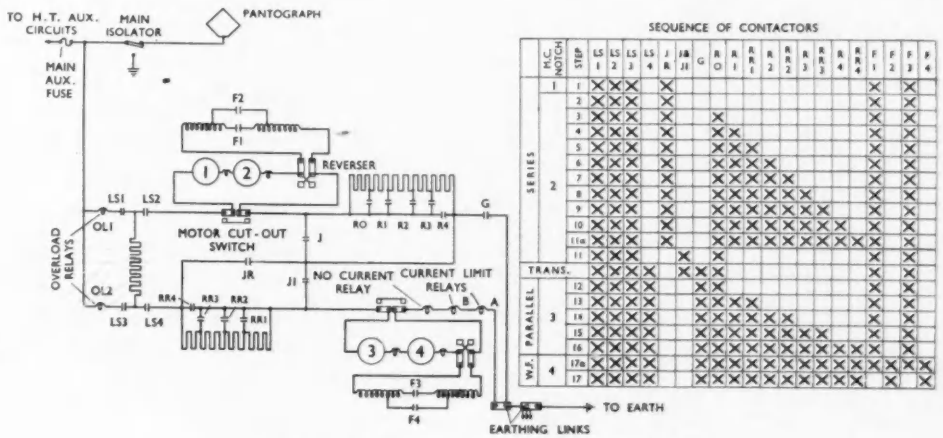


Fig. 4.—Schematic arrangement of the power circuits.

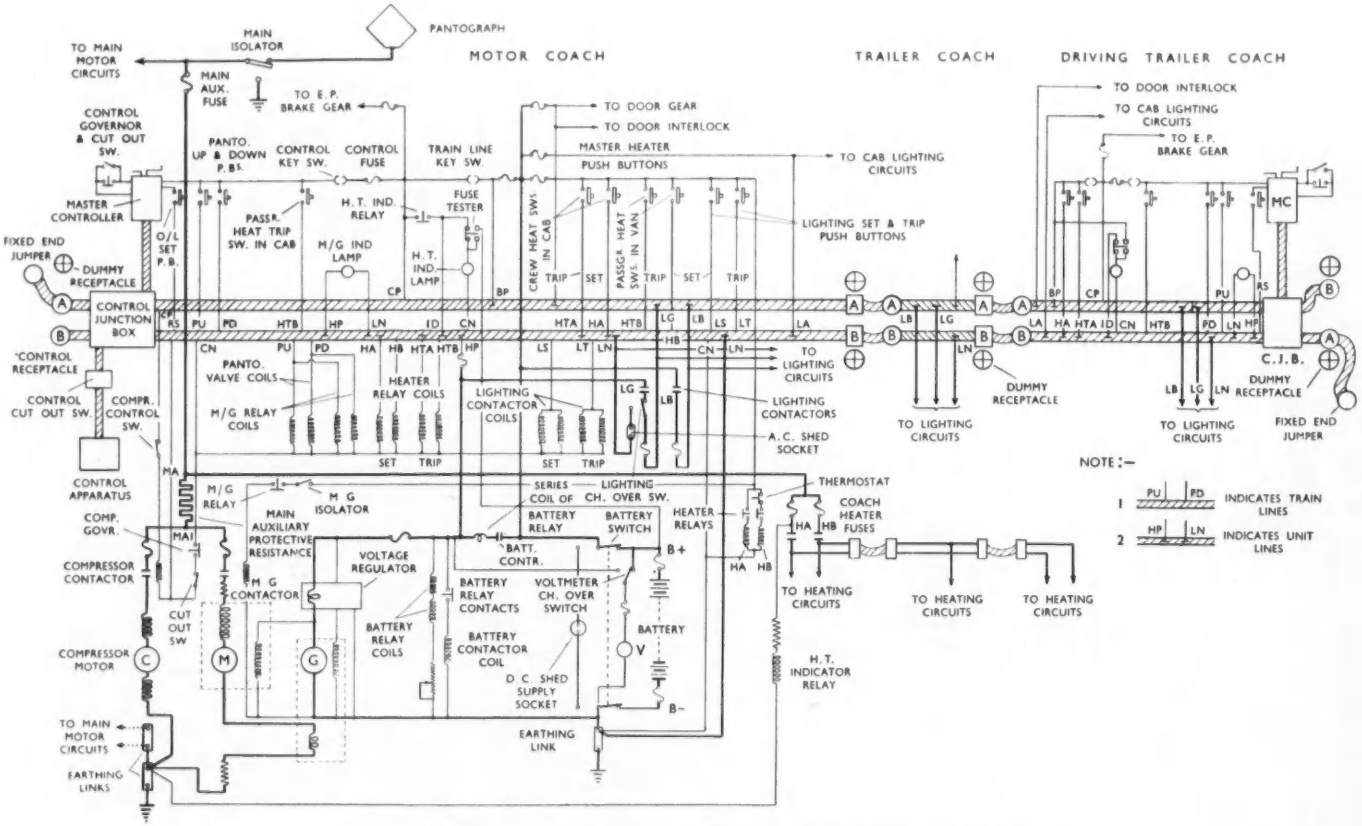


Fig. 6.—Schematic arrangement of the auxiliary power and control circuits.

TABLE 1.

	Motor Coach	Trailer Coach	Driving Trailer Coach
Length over body	60 ft. 4½ in.	55 ft. 0½ in.	55 ft. 4½ in.
Width over side panels	9 ft. 3 in.	9 ft. 3 ins.	9 ft. 3 in.
Height to top of roof	12 ft. 4½ in.	12 ft. 4½ in.	12 ft. 4½ in.
Height to top of pantograph	13 ft. 1 in.	—	—
Bogie centres	41 ft. 3 in.	38 ft. 0 in.	38 ft. 0 in.
Bogie wheel base	8 ft. 6 in.	8 ft. 0 in.	8 ft. 0 in.
Weight equipped but unladen	50·636 tons	26·424 tons	27·476 tons

isolator which, in the isolated position, earths the equipment. The motors are arranged in two groups of two motors permanently connected in series, thus they do not operate above half line voltage. Series-parallel connection of the motors is arranged, the well-proven bridge transition being adopted. Special attention has been paid to smooth acceleration, and it will be noted that a large number of resistance steps is included. In order to obtain the required maximum balancing speed and to provide a selective top speed, one degree of field tapping is arranged. Overload and fault protection is provided by the four line switches *LS*1, *LS*2, *LS*3, and *LS*4, together with the associated resistance and overload relays. Should a fault or overload occur during series connection, relay *OL*1 will operate, and line switch *LS*1 will open at once and insert the resistance. It will be followed immediately by the opening of the line switches, *LS*2 and *LS*3, which break the current. In the parallel connection, a fault or overload in one or other of the two parallel circuits will operate the circuit relay *OL*1 or *OL*2. If the fault or overload is associated with the motors 1 and 2, circuit relay *OL*1 will operate and at once open line switches *LS*1 and *LS*4. The opening of LS1 will insert resistance in the fault circuit, and is followed by line switches *LS*2 and *LS*3 breaking the current. The opening of *LS*4 simply switches off motors 3 and 4 and their associated circuit. Similarly, a fault or overload on the circuits associated with motors 3 and 4 will at once open line switches *LS*2 and *LS*3, the opening of *LS*3 inserting resistance and the opening of *LS*2 cutting off the circuits of motors 1 and 2; the opening of line switch *LS*3 is followed by *LS*1 and *LS*4 which break the current. By this means the maximum possible breaking capacity is available at the train, and the substation or feeder breakers will rarely, if ever, be called upon to clear vehicle faults. The full detailed sequence of switching during acceleration may readily be followed from the sequence chart in fig. 4, and by reference to the control diagram (fig. 7) described later.

All the switching contactors and the line switches are of a modern electro-pneumatic type and are identical, the line switches only being provided with additional arc chutes. Reversing is carried out by reversal of the motor field by means of an electro-pneumatically operated

TABLE 2.

Average distance between stations	1·31 miles
Normal accelerating rate	1·24 m.p.h./sec.
Normal braking rate	1 m.p.h./sec. above 30 m.p.h. 2 m.p.h./sec. below 30 m.p.h.
Average running speed	28·5 m.p.h.
Safe maximum speed	70 m.p.h.

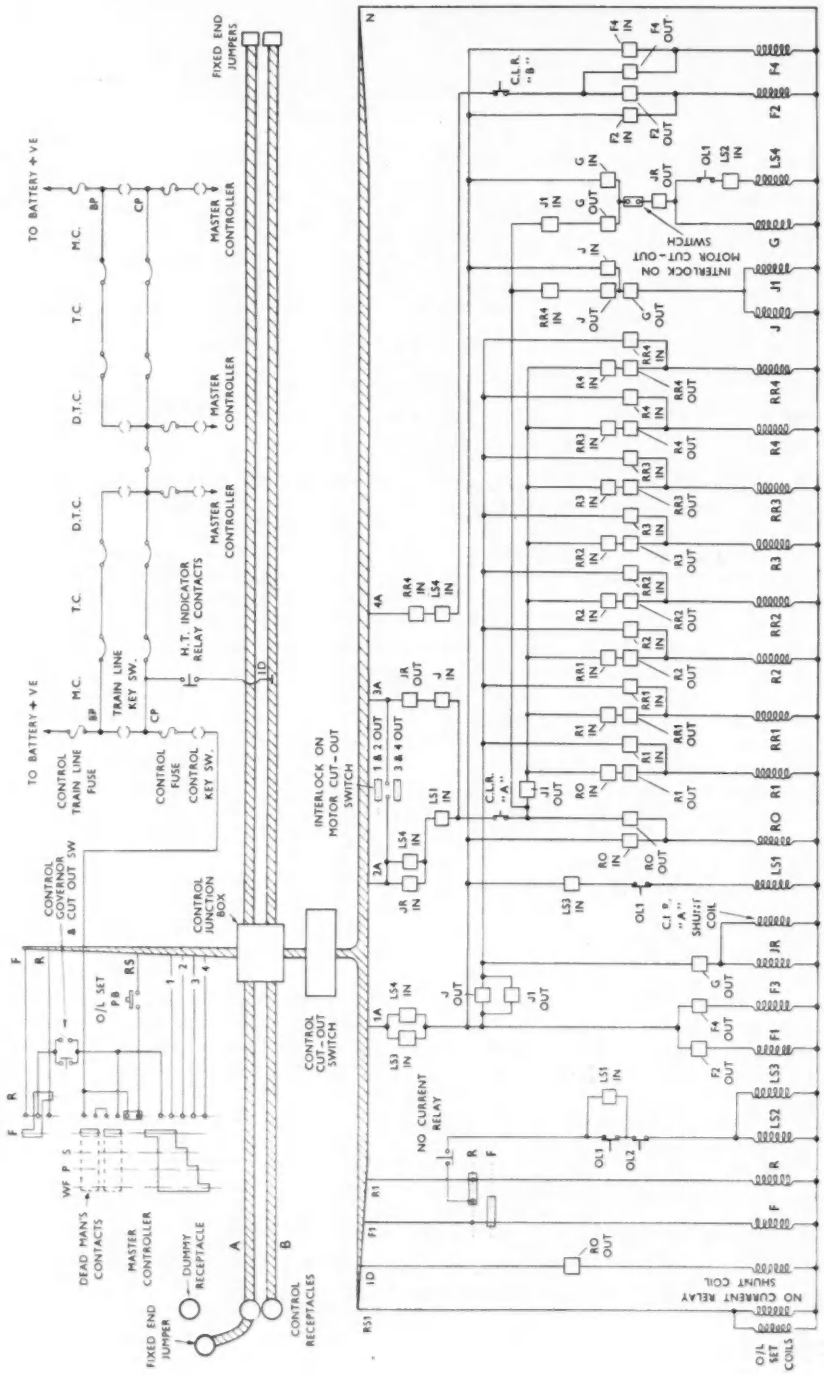


Fig. 7.—Simplified arrangement of the control scheme.

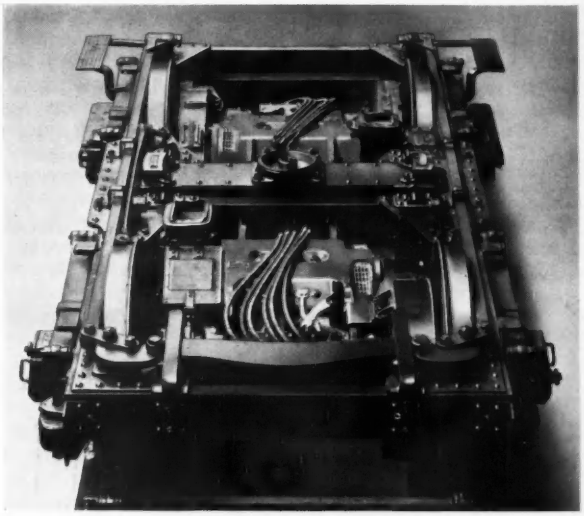


Fig. 8.—Motor coach bogie.

drum switch. In emergency, either pair of motors may be cut out by means of a hand-operated drum switch. Under these conditions a train consisting of one or more train units may be operated for a limited period to clear the line and avoid any appreciable delay. Certain earthing links are provided for testing purposes and all relays other than the overload relay are arranged on the earthed side.

Fig. 5 shows the performance curves, with the accelerating relay set for 1·24 m.p.h./sec. It will be noticed that an easy shunting step, namely step one, is provided for marshalling trains in depots, etc. The normal automatic notching up to full field parallel (step 16) has been arranged to give very smooth acceleration avoiding any excessive peaks ; in all, fourteen steps are provided. If the driver utilises automatic acceleration to the weak field (step 17) an excessive peak is avoided in passing from step 16 to 17 by using a second accelerating relay having a lower setting. This obviates the undesirable complication of introducing a resistance step between steps 16 and 17. In actual practice the calculated peak values are rarely, if ever, obtained, due to inductive and other effects, consequently the performance curves may be regarded as very satisfactory. Both test and service running have so far fully endorsed this. Since the driver may run continuously on either full series (step 11), full parallel full field (step 16), or full parallel weak field (step 17), he has very ample control of speed. Balancing speeds on level for steps 16 and 17 are not shown, but are approximately 58 and 67 m.p.h. respectively, empty.

AUXILIARY POWER, HEATING AND LIGHTING.

Any type of multi-unit stock presents some difficulties in the design of the auxiliary power and control scheme, and this has considerable influence upon reliability in service, ease of maintenance, and passenger comfort.

The auxiliary power and control circuits are shown in schematic form in fig. 6, and it should be mentioned that a low voltage of 52 is available for all control, battery charging and lighting circuits. The 1,500 volt feed is taken from the dead side of the main isolator and passes through a special high duty fuse, which functions as the main protection. A feed is then taken off to the 1,500 volt train heating circuits referred to later, and one to the protective resistance on the positive side of the two 1,500 volt motors, namely those of the compressor and the L.T. generator. This resistance not only limits the short circuit current in the rare event of a bad fault, but also limits the starting peaks by adding

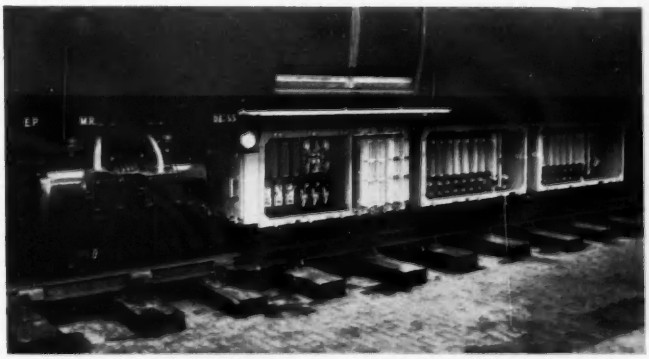


Fig. 9.—Arrangement of the equipment cases on the under frame.

to the series resistance of the M.G. set motor. Each machine is provided with its own fuse, so that a fault on either does not affect the remaining 1,500 volt circuits. Both machines are directly started from the supply by the closing of their respective electromagnetic contactors by low voltage solenoids. A description of the master circuits is given later. The compressor is a straight series machine, while the motor of the M.G. set is mainly a series machine, but is provided also with a shunt field excited from the source of supply is available. It should be noted that the remaining lighting circuits are energised direct from the L.T. generator so as to avoid undue demand on the battery in an emergency. In addition, essential power and brake control circuits may be energised from another train unit supply in the event of abnormal emergency. This is referred to later when the control circuits are described.

As mentioned, the heating circuits are fed at line voltage from the positive side of the protec-

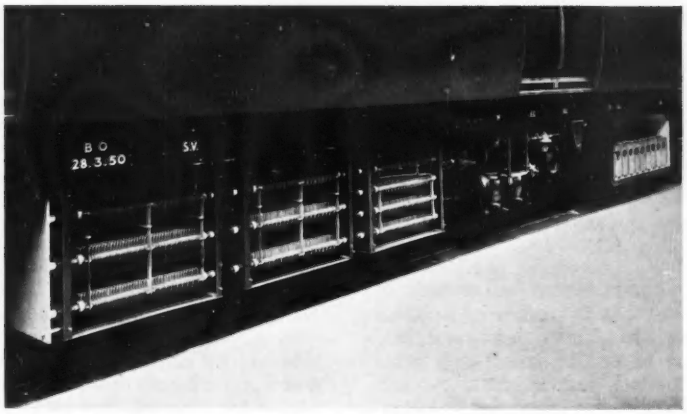


Fig. 10.—Arrangement of the main resistors and battery on the under frame.

L.T. generator. This has the effect of limiting the speed range, while the sections of series resistances give a high factor of stability on sudden variations of line voltage. The L.T. generator has a rating of 6 kW at 52 volts over a range of 1,000 to 1,800 line volts. At 750 volts line pressure there is a small drop in the L.T. volts. but not sufficient to interfere with essential services in this abnormal emergency condition. The L.T. voltage is controlled by a special type of carbon pile regulator having a characteristic suitable for floating in parallel with a nickel-iron battery under all conditions. The battery consists of 33 Nife cells, type ES12, of 125 Ah capacity at the five-hour rating. A polarised battery relay associated with a contactor maintains the parallel interconnection of battery and L.T. generator so long as the voltage is suitable.

To prevent failure of either the battery or M.G. set from affecting the running of the train, all master control circuits and a section of the lighting circuit are energised from the battery side of the paralleling contactor, and consequently remain energised so long as one or other tive resistance from which point the whole train unit is fed, the trailer and driving trailer coaches being fed by semi-permanent bolted-up jumpers. No heating connections are carried between train units. This avoids the introduction of complicated interlocked jumpers between train units, which would otherwise be needed to avoid danger to the staff when making up trains for service.

Each coach is provided with twenty-one 400 watt heaters arranged in three circuits of seven in series. They are of special design to avoid danger to passengers. The 1,500 volt train unit heater feed is divided into two circuits, each having its own fuses and contactor situated in the motor coach. One feeds two circuits of seven heaters on both motor coach and driving trailer and three in the trailer coach ; the other feeds a circuit of seven heaters in the motor coach including heaters for the guard's compartment and the driver's cab and a circuit of seven on the driving trailer coach including driver's cab heaters. The contactor controlling the major circuit is under the control of the guard by means

of push buttons in the guard's compartment, and a set-and-trip relay associated with the electromagnetic contactor. The contactor controlling the greater number of heaters is also governed by a thermostat, only three passenger heaters in the motor coach and five in the driving trailer not being thermostatically controlled. By this arrangement the heating of passenger compartments is virtually thermostatically controlled and the driver has individual control over the driver's cab and guard's compartment. This allows the use of a simple scheme and one type of heater without appreciable sacrifice of energy when trains are not carrying passengers.

To meet any emergency, the driver can trip out all heater circuits by means of a push button in his cab. The lighting is arranged in two circuits on each train unit, a limited number of lights being fed direct from the battery for emergency lighting. In addition, and on individual circuits, there are the various lights for the markers, cabs, guard's compartment, tail, and instruments. The passenger compartments of the motor, trailer and driving trailer coaches are provided with 22, 26 and 24, 60-watt lamps respectively, resulting in a very satisfactory level of illumination. All circuits are suitably fused and the passenger lights throughout any train make-up are under the control of the guard by means of push buttons associated with set-and trip relays and L.T. electromagnetic contactors. A change-over switch and plug allow most of the lights to be fed from a shed supply during cleaning and maintenance.

CONTROL SCHEME.

Before the machines and apparatus are dealt with, it will be of interest to consider some details of the control scheme which is shown in a simplified form in fig. 7. The driver is provided with a train line key and a control key as well as the usual reverse key. His train line key may be used to operate any train line key switch in any driving position of the train. This switch, when operated, connects the L.T. train line to the train unit supply line of the train unit in which the switch is operated. From this line a feed to the master controller can be obtained by the use of the control key. This arrangement has the advantage that, in the very rare event of a failure of both battery and M.G. set, a train of two or more train units may be driven from any driver's cab so long as the train line key is used to close a switch on a sound train unit, thereby energising the control train line "C.P.". In no circumstances can the L.T. systems of the train units be paralleled.

The master controller is provided with a main handle having an "off", "first step" for shunting and coupling up, a "series step" giving automatic control to full series full field, a "parallel step" giving automatic acceleration to full parallel full field, and a weak field step giving automatic acceleration to full parallel weak field. The automatic features are such that there is no need to pause on any position. The main handle is provided with a dead man's button, associated with the handle grip, which in the event of the collapse of the driver will operate

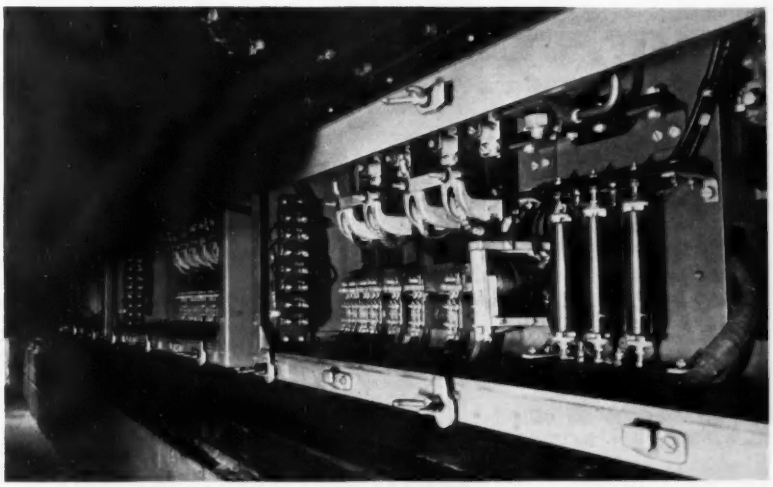


Fig. 11.—Rear of equipment cases with covers removed showing accessibility from the maintenance pit.

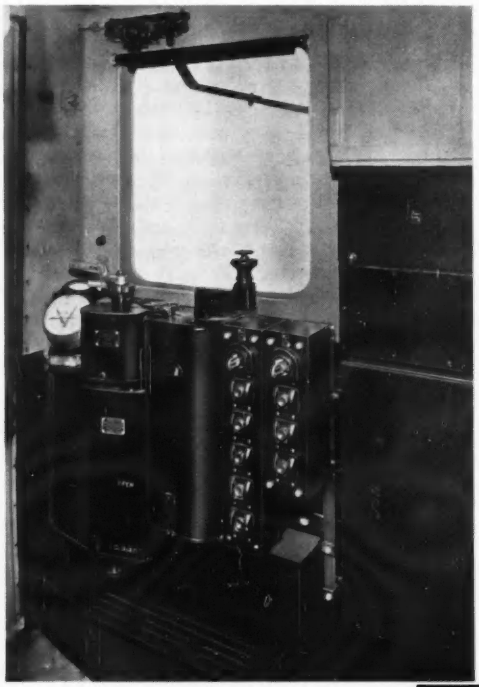


Fig. 12 (*above*).—Interior of the driver's cab showing the driver's position.

and switch off all power and, by the operation of a pilot valve, will give an emergency application of the brakes. The main handle and the reverser, which is operated by the driver's reverse key, are so mechanically interlocked that the reverser drum can be operated only when the main handle has switched off power. When the reverser key is removed, the main handle is locked in the "off" position and the dead man's equipment made inoperative. Thus, without the key, the controller is completely inoperative, but any other controller on the train may be used by inserting the key. Should the line switches open on a fault or overload they may be reset by pressing a button by the side of the controller, but only after the main handle has been brought to the "off" position.

Electrical interlocks are provided on the reverser and contactors, so that the power circuits may not be formed until the reverser has been fully thrown to the position corresponding to that of the master controller, and contactors can only close in the correct sequence. In addition interlocks ensure the transition being automatically carried out, and the correct operation of the line switches on overload or fault. Lastly, interlocks are provided to ensure that should certain contactors fail to open, no dangerous circuit conditions can arise. Contacts associated with the motor cut-out switches modify the control circuits in a suitable way when motors are cut out. Since parallel combination only is possible on the faulty train unit, the train as a whole is prevented from operating in series, although series combination remains operative as an accelerating feature on the sound train units.

Should some serious control faults develop, the control circuits may be isolated by a multipoint cut-out switch, which permits the remainder of the train to be driven by the master controller and associated controls at either end of the faulty train unit. No-volt protection is provided by a no-current relay. This is set by an

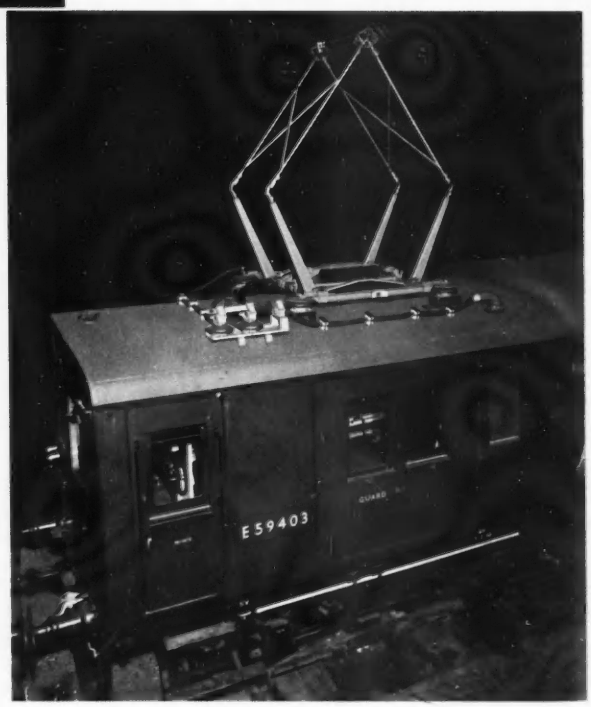
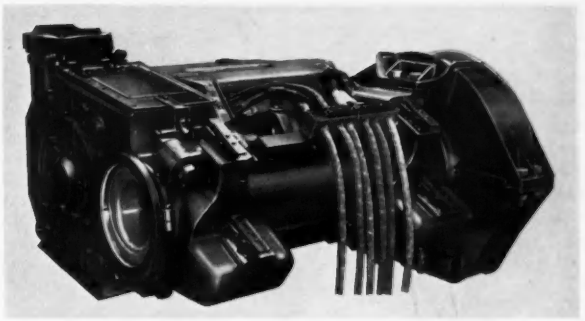


Fig. 13 (*right*).—Pantograph and main isolating switch on the roof of the motor coach.

L.T. shunt coil controlled by interlocks on the H.T. indicator relay. The coil is cut out on all except the "off" and first steps, and the relay retained by a series coil carrying motor current. Any failure of line voltage will at once operate the relay and power will be cut off. On restoration of the line voltage, the equipment will notch up automatically if the driver has not switched off. Alteration to the setting of the current limit relay for parallel running is entirely automatic. Two sets of train lines with bifurcated couplers at the ends of train units carry all master control circuits for power operation and auxiliaries. Pantograph operation is by means of push button.

LAYOUT OF EQUIPMENT.

The general layout of the equipment may be seen from figs. 8, 9, 10, 11, 12 and 13. Fig. 8 shows the two axle hung motors mounted in a motor coach bogie, while fig. 9 shows the three equipment cases, with covers removed, mounted on



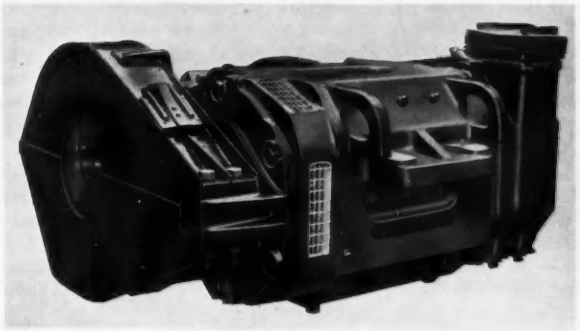


Fig. 15 *(upper)*.—Motor from the commutator end.

Fig. 16 *(lower)*.—Motor showing the gear casing.

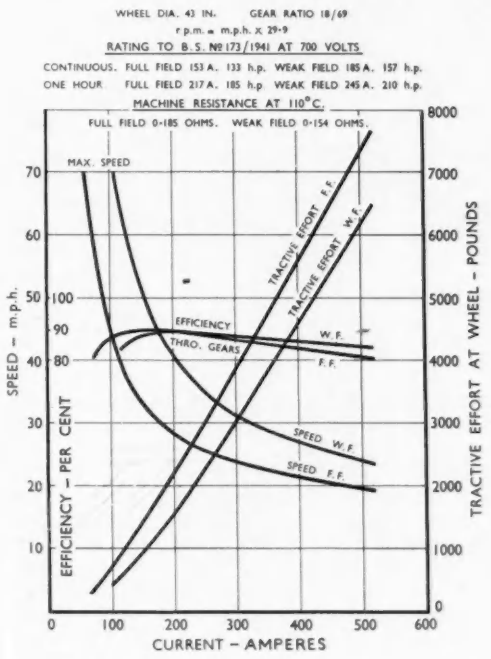


Fig. 14 *(left)*.—Motor characteristic curves.

one side of the under frame. The two cases at the right clearly show the main contactors, the reverser and certain relays; the case on the left shows the extended arc chutes of the four line switches with sundry relays and the four 1,500 volt auxiliary contactors. The H.T. fuses are situated in the case on the left facing the motor generator set, which is suspended by resilient mountings. The main resistances and battery are mounted on the other side of the underframe, and may be seen with covers removed in fig. 10. Between them are mounted certain compressed air details.

Covers at the back of the cases give access from inspection pits for maintenance. The easy accessibility is clearly shown in fig. 11. The compact and convenient arrangement of the driver's position is readily appreciated by reference to fig. 12. To the left are the brake gauge and brake valve, in the centre is the master controller and to the right the key switches and control push buttons. Fig. 13 shows the arrange-

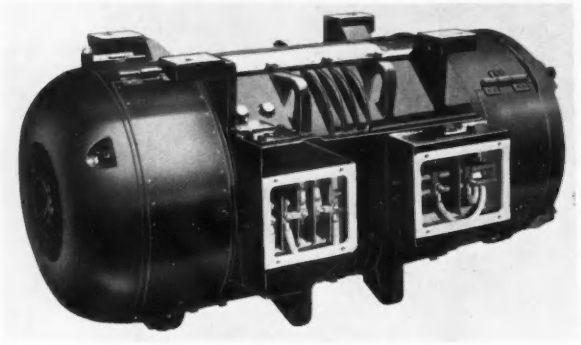


Fig. 17.—Motor-generator set.

ments of the pantograph and main isolating switch on the roof of the motor coach.

In a general description of the trains and their equipment it is not possible to refer in detail to the many special features of design and manufacture of the machines and apparatus, but what follows will, it is hoped, convey some picture of the design and manufacture of the components.

MACHINES.

Each main motor has the following ratings at 700 volts based on British Standard No. 173/1941:

Continuous full field: 133 h.p., 153 amps, 985 r.p.m.

Continuous weak field: 157 h.p., 185 amps, 1,290 r.p.m.

One hour full field: 185 h.p. 217 amps, 815 r.p.m.

One hour weak field: 210 h.p. 245 amps, 1,055 r.p.m.

The motors are of the 4-pole series wound type arranged for self-ventilation from intake louvres mounted high up on the sides of the coach. Fig. 14 shows their characteristic curves. Their construction may be seen from figs. 15 and 16. Fig. 15 shows the commutator end and the suspension bearings, which are of the sleeve type, oil-lubricated by means of cotton packing. Access to the commutator is available through two large covers, one on the top and one on the bottom of the housing. The bellows for the air intake from the coach ducting are clearly visible. Fig. 16 shows the nose for suspension from the bogie, the ventilating air outlets, and the gear case, which is of fabricated construction, the gearing itself being of the single reduction spur type.

The armature is carried in grease-lubricated roller bearings, and can be removed from the motor frame without opening up the bearing assemblies, so that there is no fear of dirt entering the housings during this operation.

Hard mica wraps moulded on to the coils serve to insulate the slot portions of the armature windings, and during manufacture the windings and insulation are consolidated while hot into a solid mass by means of a banding process, all interstices being filled with an insulating cement. On the completion of this process, the armature coil retaining bands, of high tensile steel wire, are applied.

The field coils are formed from copper strip, with interturn insulation of treated asbestos, the main insulation consisting of cambric-backed mica with an outer taping of asbestos. They are impregnated with synthetic resin varnish which is then polymerised and thus produces coils of great strength with excellent insulating and heat dissipating properties.

Each brush box is carried on an insulated bar, clamped at each end to the motor frame. Provision is made for radial movement to allow for commutator wear, but the brush boxes are accurately located circumferentially by dowels.

Fig. 18.—Single pan pantograph.

MOTOR-GENERATOR SET.

The motor-generator set is rated at 6 kW at 52 volts, the L.T. voltage being regulated by a carbon pile regulator. The set is shown in fig. 17 with terminal box covers removed. At each end the covers for the L.T. and H.T. commutators may be seen, while on the top are the suspension lugs for the resilient mounting

units, one of which is shown in fig. 17. The method of construction conforms to standard traction practice, and is closely similar to that of the main motors.

The H.T. motor and L.T. generator are combined in a single machine having two bearings only of the roller bearing type. The set is totally enclosed with an external centrifugal fan at the L.T. end, arranged so as to blow air along the outside of the ribbed frame.

The motor is a 2-pole compound wound machine with a shunt field fed from the 52 volt supply; the generator is a 4-pole machine without interpoles.

APPARATUS.

The pantograph current collector may be regarded as one of the most important items of equipment, since poor operation not only causes wear to the line and the pantograph, but may easily cause trouble on the machines and apparatus.

The single pan light weight pantograph has previously proved satisfactory in operation; the light weight construction is shown in fig. 18 and it will be seen that it is built on a light steel frame supported from the roof by insulators. The four bottom arms are of pressed steel and are rigidly welded to two transverse tubes carried on four arbor bearings. The upper arms are of tube construction pivoted together at the apex. The steel pan is sprung to the apex by a simple lever arrangement the lower arms of which are carried on two transverse torque bars. By this means the pan can follow small line irregularities without moving the main pantograph frame, and due to the torque bars the pan always remains parallel to the mounting plane, which has the effect of obtaining better clearance in tunnels.

The pan is permitted a small amount of free tilting so that it always beds on the line. The pan mounting pins are arranged as close to the pan as possible to reduce pressure transfer from the trailing to the leading edge. The collecting surfaces are formed of copper strips, those at the edges being lipped over the pan to avoid burning of the pan.

The pantograph is maintained in its up position by the two open springs, which exert an inward pull on the cranks fixed to the bottom transverse tubes. The pantograph is lowered by

Fig. 19.—Main electro-pneumatic contactor.

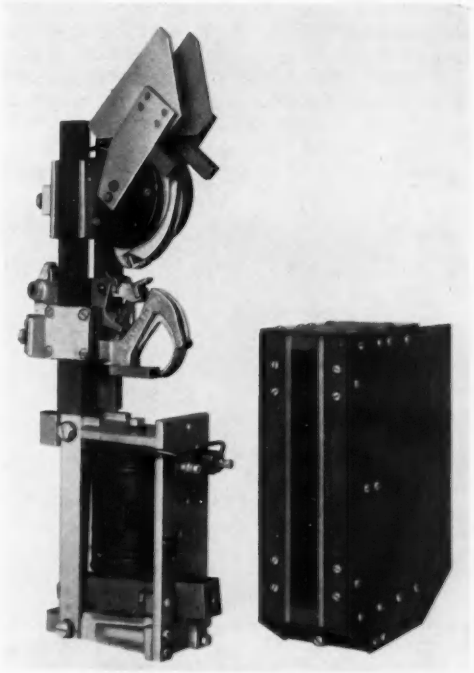


Fig. 20.—1,500 volt auxiliary contactor.

an overruling spring contained in the centre cylinder. Thus, to raise it, air is admitted to the centre cylinder thereby compressing the down spring and leaving the up springs entirely free to operate.

Ball bearings are extensively used in the joints to reduce friction and all are carefully shunted by copper braids. Lubrication is by grease nipples and the pan is designed to carry any of the special lubricating greases or paints.

The construction of the main electro-pneumatic contactor is seen in fig. 19 which shows the arc chute removed and the blow out plates swung up for inspection. The unit is built on insulating steel side bars. The operating cylinder is mounted at the bottom and connected to the moving contact by means of an insulator. The moving contact tip is carried on a knuckling piece to give the required tipping and rubbing action, but is also designed to use the full piston thrust when finally closed. The fixed contact is associated with the blow out coil. Both contacts are provided with very carefully designed arc horns. Main connections and interlocks are arranged at the back and the electro-pneumatic valve at the front. The construction of other contactors for both the 1,500 volt and 52 volt auxiliary circuits follows similar lines, all types being electromagnetically operated and the L.T. type being provided with a simpler form of arc chute. Fig. 20 shows the 1,500 volt auxiliary contactor with arc chute removed and blow out pole plates swung up for inspection. Fig. 21 shows an L.T. contactor with arc chute removed and arranged for set-and-trip operation. The normal operating coil in the main frame functions as the set coil and the coil underneath as the trip coil, the contactor in this case being provided with a mechanical latch.

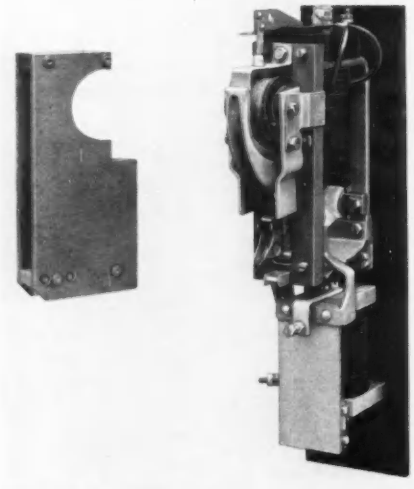


Fig. 21.—L.T. contactor with arc chute removed.

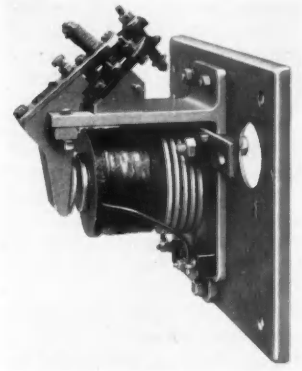


Fig. 22.—No-volt/no-current relay.

The general design features of the various relays and other small components are illustrated in figs. 22 and 23, which show the no-volt/no-current relay and current limit relay unit respectively. The use of pressings and simple fabricated parts gives a high degree of robustness, while maintaining lightness in weight. Fig. 24 shows the master controller with covers removed. On the right, one set of push buttons and key

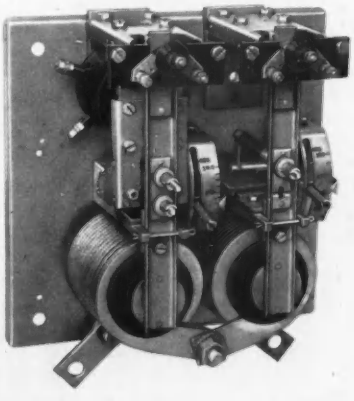


Fig. 23.—Current limit relay.

switch has the covers removed, while underneath, the terminals of the connection board can be clearly seen. With this arrangement any master controller or group key switch and push buttons can be quickly removed for maintenance.

CONCLUSION.

In conclusion it can be recorded that although the service has not long been open, coaches have been operating for some months under service conditions in order to train the drivers, and both coaches and electrical equipment have given every satisfaction.

On weekdays there is a half-hourly service to all stations between Glossop and Manchester. Between Hadfield and Manchester there is a half-hourly service morning and evening, and hourly in between these periods. Two units, namely six coaches, operate at peak hours.

Since electrification the number of trains between Glossop and Manchester has increased from seventeen to thirty-one, and from Hadfield to Manchester from ten to twenty-three. The journey time has been reduced by fourteen minutes.

ACKNOWLEDGMENT.

Acknowledgment is made to the British Transport Commission for their assistance in the preparation of this article and for their permission to publish the foregoing information and illustrations.

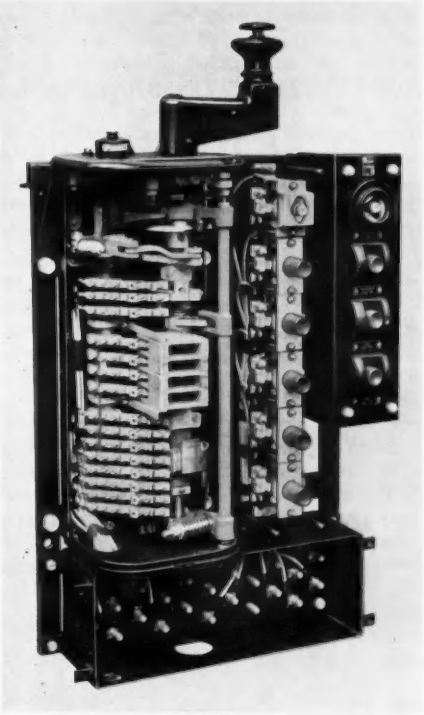


Fig. 24. —Master controller with covers removed.

Mercury Floodlighting in Canada

The first installation of mercury floodlighting in Toronto has recently been supplied by The British General Electric Co. (Canadian) Ltd. for the premises of the Standard Motor Company (Canada) Ltd., which faces the busy Queen Elizabeth Highway linking Toronto and Niagara.

Standardisation of Lift Control Systems

By W. A. DIXIE, Chief Engineer,
The Express Lift Company Ltd.

The various systems under which passenger and goods lifts operate are frequently confusing to architects and engineers who have the responsibility of choosing the one most suitable for a particular building.

In this article the author traces the evolution of the electrically operated lift and undertakes a logical analysis of the various systems now available. These are finally tabulated so that their relationship and functions can easily be understood.

INTRODUCTION.

THE apparently extensive range of systems under which passenger lifts can operate must be confusing at times to the architect or engineer who has to decide what is required for a particular building. If he seeks advice, he will quite likely get many different answers. This is due to several causes, the chief of which is that it is very rarely that anyone has had the opportunity, or taken the trouble, to analyse thoroughly the systems available.

After a comparative and functional study of the various methods of controlling passenger and goods lifts, an impression may be formed of fine distinctions and a lack of logical reasoning for the continued existence of some traditional practices.

An effort is now made to present the subject in a practical and simple way to demonstrate that there is a possibility of standardising the grouping and nomenclature of control systems in a self-explanatory and logical manner.

The method of presentation used is to tabulate the systems in such a way that their relationship to one another and their function are seen at a glance.

EARLY DEVELOPMENT.

The original classification was into attendant-operated and passenger-operated systems. The early lifts always needed an attendant in charge, as a certain amount of skill in operation was required. The first lifts in common use were hydraulic and a rope passed through the car so that the attendant could operate the correct valves by pulling this rope up or down according to the direction in which it was desired to travel.

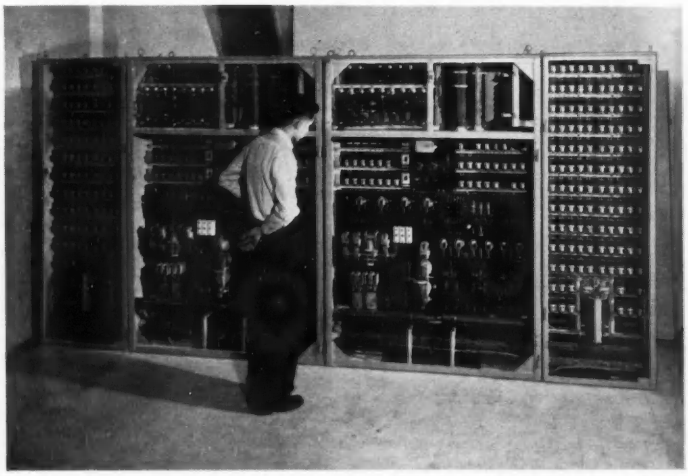


Fig. 1.—The controllers for a pair of high-speed lifts in Hong Kong using a multiple call control for two cars.

To stop the lift, the attendant held on to the rope, and due to the motion of the car, this had the effect of closing the opened valve. The accuracy with which the car stopped at floor level depended on the speed of the lift and the skill of the attendant.

When the first electrically powered lifts were installed it was natural that at first the rope control should be retained. It was not long, however, before the electric supply was carried to the car by means of trailing cables. A car switch then replaced the rope for controlling the movement of the car. The car switch handle could be moved only from the neutral to the up or down position. As soon as the handle was released, it would be returned to the neutral position by springs. An attendant was still required for every lift.

The higher the speed of the lift, the more difficult it was for the attendant to judge accurately the correct instant for returning his car switch handle to the neutral or " off " position. This difficulty was overcome by using two-speed motors and giving the car switch high- and low-speed points in both directions of travel. The attendant could start the lift by moving directly over to the high-speed position in the required direction, but for landing he would first return his switch to the low-speed position and then finally release to the " off " position when the lift was travelling at the low speed. His chances of stopping level at the floor were thereby greatly increased.

This type of operation is known as car switch control with manual stopping, irrespective of whether a one-, two- or multiple-speed motor or system is used.

Intending passengers on the landing could register their calls by pressing the landing call button which registered the floor number on an indicator in the car. The attendant could reset the indicator when he had answered all calls.

The limitations of the car switch lifts operated by attendants soon became apparent on lifts in busy office buildings. The attendant had to watch his indicator of landing calls carefully and at the same time remember the floors at which his car passengers wished to stop. All this was in addition to concentrating on the efficient operation of the lift itself. Several improvements came to the attendant's aid. The landing calls were automatically cancelled on his car indicator as they were answered. The car would automatically slow and stop at the next floor after the attendant had centred or released his car switch. This was the result of the introduction of the necessary switchgear to give automatic landing.

A demand soon became evident for a slow-speed lift which could be operated by the passengers themselves. As soon as the necessary switchgear was devised to stop the lift automatically at the desired floor, push buttons, one for each floor, were fixed in the car, together with a single call button at each landing. Provided all the entrances were properly closed, momentary pressure on one of these buttons would cause the lift to travel to the floor represented by the button pressed. There would also be a call button at each landing, the operation of which would cause the lift to come to the required floor, provided, again, that all entrances were closed and that the lift was not already being used.

The greater accuracy of stopping at floors by using two-speed motors was soon applied to passenger-operated lifts, but the whole operation of floor selection, slowing to a levelling speed, and then stopping, had to be done automatically.

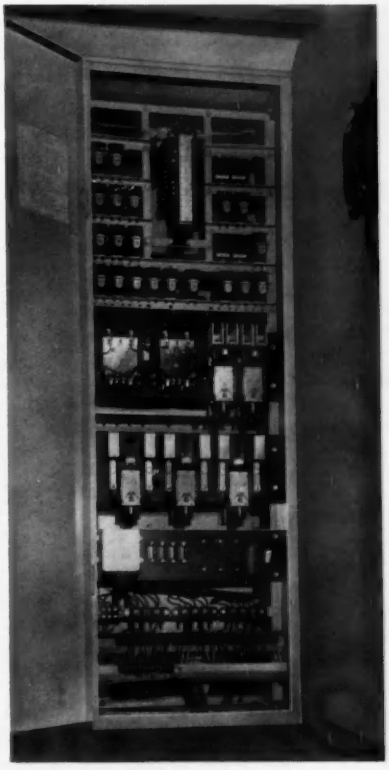


Fig. 2.—The controller for a lift using a single call control.

The limitation of these passenger-operated lifts was the " taxi service " they gave from one floor to another irrespective of any service that might be required from an intermediate floor.

In some situations it was a convenience if a car switch attendant-operated lift could be used by the passenger without an attendant during the slack periods of the day. This led to what was known as dual or car switch dual control. The car control panel carried all the equipment

Fig. 3.—One of over 500 passenger perambulator lifts recently ordered from the Express Lift Co. Ltd. Passenger single call control.

required for both systems, together with a key-operated transfer switch. When attendant-operated, the landing call buttons operated the car indicator, and when passenger-operated they controlled the lift if available. Either the car switch or the floor buttons in the car were operative, but not both.

Some owners of automatic passenger-operated lifts wanted to improve their service at certain times by putting them in charge of an attendant. To make this a practical improvement, a call indicator was added to the car and a key-operated transfer switch. When the attendant took charge and set the transfer switch to attendant-operation, the landing buttons were changed over from operating the lift to registering calls on the car indicator. The attendant operated the lift by means of the floor pushes in the car, i.e. a push button for each floor, in the same way as a passenger would do. This system was called " semi-dual " or " modified dual ". The qualification of dual control was justified, since once the attendant had pressed a push for a floor well ahead, and a landing call then registered on his indicator for a floor nearer to him but in the same direction as he was travelling, the lift could not normally be stopped at the nearer floor. In other words, the service given was not quite so good as car switch dual.

SIGNAL AND COLLECTOR SYSTEMS.

Signal control was a natural development of the car switch attendant-operated lift. The landing calls or signals were still registered on the car call indicator, but were also registered in the controller located in the machine room. The controller was so arranged that it stopped the lift automatically to answer these landing signals. The landings had two call buttons, one above the other. The upper button, marked " up ", was pressed if the passenger wished to travel upwards; the lower button was correspondingly marked " down ". This enabled the controller to distinguish between up and down landing signals so that when the car was travelling upwards it would answer only up calls and ignore down calls, and vice versa when moving downwards.

This ability of the controller to register and store landing calls was extended to include the car passengers' destinations. As the passengers entered the car, they each gave their floor destinations to the attendant and he registered them by pressing the corresponding floor buttons on the car control panel.

With power-operated doors, the attendant's duties in a signal control lift were reduced to operating a starting handle in the direction in which the lift was to travel. All the stopping of the car (both for passengers waiting on the landings and for those travelling in the car) was looked after by the controller. The result was a great improvement in the efficient handling of the traffic. Landing calls were not overlooked and car passengers were not taken past their floors, as so easily happened with a car switch controlled lift.

The circuit principles evolved to bring about this registering of landing and car calls, could now be used to improve the simple passenger-operated or automatic lift. Just as the car switch

lift became the signal control lift, in order to handle a greater number of passengers, so the automatic lift became the collector lift to give a lift service to a greater number of people.

The collector lift was arranged to collect passengers from intermediate floors who had put in calls for the direction in which the car happened to be travelling. Thus intending passengers on the landing used "up" and "down" buttons just as for signal control lifts, and with the same result. As the passengers entered the car, they would register their own car calls, since there would be no attendant in a collector lift.

Each time a passenger entered a car and registered a car call, the lift would start and would very likely stop on the way to collect others wishing to travel in the same direction. If the last car passenger got out and there was another landing call waiting to be answered, the lift would automatically start, after a suitable interval, to answer that call and so on until every call in the system had been met.

It will be quite obvious that from the design and equipment point of view these two controls (signal and collector) are very similar. Therefore, when the need arose to be able to operate the same lift as a signal or collector lift, the amount of additional equipment needed was very small. However, fine distinctions were drawn. For instance, a lift which was generally operated by an attendant, but only occasionally by the passengers, was known as a signal control lift with night service, since it was generally only at night time that passenger operation would be required. Likewise, a lift which was generally operated by the passengers, but had the ability to be operated by an attendant for extra busy periods or special occasions, was known as a collector control lift with attendant service. To preserve the illusion of a difference in systems, the collector lift had an "up" and "down" button in the car for the attendant's use, instead of the starting handle of the signal lift. There were also other minor differences which did not really merit the retention of so many differently named systems. The desire for simplification in nomenclature has had good results, as will be seen a little later on.

METHODS OF GROUPING CONTROL SYSTEMS.

Meanwhile, it is as well here to recapitulate and show in tabulated form the existing control systems already outlined. These are seen in diagram 1. It will be noticed that there are two methods of operation, i.e. attendant and passen-

Fig. 4.—Two high-speed office lifts using a multiple call control for two cars.

ger, resulting in four basic control systems and four combination or dual controls.

These systems can be shown in another way. Diagram 1 groups car switch and automatic controls together and denotes them as " Single Call Controls ". This is logical, since the lift system in each case cannot deal with more than one call at a time. It also groups signal and collector controls together under the heading " Multiple Call Controls ". The reasoning here is due to the ability of the lift system to register a multiplicity of calls and to continue in operation until all calls in the system have been answered.

In the early days of the development of electric lifts, the emphasis was on the difference in capital cost between an attendant- and a passenger-operated lift. The extra equipment needed for an automatic lift was expensive and its upkeep added to the maintenance costs. In those days, wages for an attendant were low and interest on capital was high. Today the position is reversed. When the multiple call systems are considered, it has been pointed out already that there is very little difference in equipment, and so in first cost, between an attendant-operated and a passenger-operated lift. However, there is a decided difference in the amount of controller equipment required between a single and a multiple call system. There is also a marked difference in the type of service which these two kinds of lifts can be expected to give.

It is therefore suggested that a more up-to-date picture would be drawn if the emphasis on operation, with or without an attendant, were dropped in favour of single and multiple call systems. Herein lies the real difference in type of service given and in the cost of the system. In other words, instead of four basic systems such as car switch, automatic, signal, collector, together with their several combinations of dual control, there could be a reduction to two principal systems with a minimum number of variations.

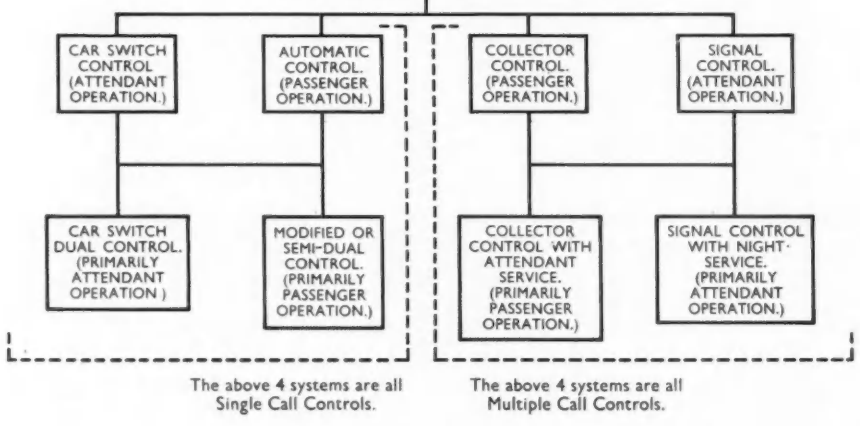
The lower part of diagram 1 shows this simplified grouping of control systems under the headings " Single Call Controls " and " Multiple Call Controls ".

EXISTING INTER-CONNECTED CONTROL SYSTEMS.

It is axiomatic that when two or more lifts are adjacent to one another so as to form a single vertical transport unit, then their individual control systems must be so inter-connected

DIAGRAM 1

EXISTING CONTROL SYSTEMS FOR ONE-CAR INSTALLATIONS.


CAR SWITCH CONTROL (ATTENDANT OPERATION.)
AUTOMATIC CONTROL. (PASSENGER OPERATION.)
COLLECTOR CONTROL. (PASSENGER OPERATION.)
SIGNAL CONTROL. (ATTENDANT OPERATION.)
CAR SWITCH DUAL CONTROL. (PRIMARILY ATTENDANT OPERATION.)
MODIFIED OR SEMI-DUAL CONTROL. (PRIMARILY PASSENGER OPERATION.)
COLLECTOR CONTROL WITH ATTENDANT SERVICE. (PRIMARILY PASSENGER OPERATION.)
SIGNAL CONTROL WITH NIGHT SERVICE. (PRIMARILY ATTENDANT OPERATION.)
The above 4 systems are all Single Call Controls.
The above 4 systems are all Multiple Call Controls.

The diagram shows how the existing 8 control systems for one-car installations fall naturally into 2 main groups—Single and Multiple Call Controls. Car Switch and Modified Dual Controls are easily combined into one system. This also applies to the 4 Multiple Call Controls, since the equipment is very similar in all 4 cases.

that they function as a whole, rather than as separate units. It is also generally agreed that such installations should use signal or collector control lifts. Diagram 2 shows the systems in use for two, three, four or more car banks, together with their respective dual control systems.

It has already been pointed out that signal control with night service and collector control with attendant service are very similar in equipment and operation. The same similarity holds good irrespective of the number of cars in the group of lifts. However, for two and three car banks, there exists a choice of eight different controls, as set out in diagram 2.

There is no point in tabulating the various systems offered in conjunction with four or more cars, because, being proprietary, their names bear little connection with their operation. These names are evidently chosen with an eye to their supposed sales value.

The alternative descriptions, "duplex," "triplex" and "collective" are tabulated. The styles "duplex" and "triplex" are somewhat restricted, although an attempt has been made to use "quadruplex". Fortunately, for more than four cars, no attempt has been made to extend this style. The word "collective" is unfortunate when used with the adjective "selective" to distinguish a directional collector control from a down collector control. Down collector control is a special form of collector control in which the collector feature functions only while the lift is travelling in the down direction. It is sometimes used in flats when all landing calls above the ground are assumed to be for a down direction of travel. A directional or selective collector control denotes that the collector feature functions for both directions of travel.

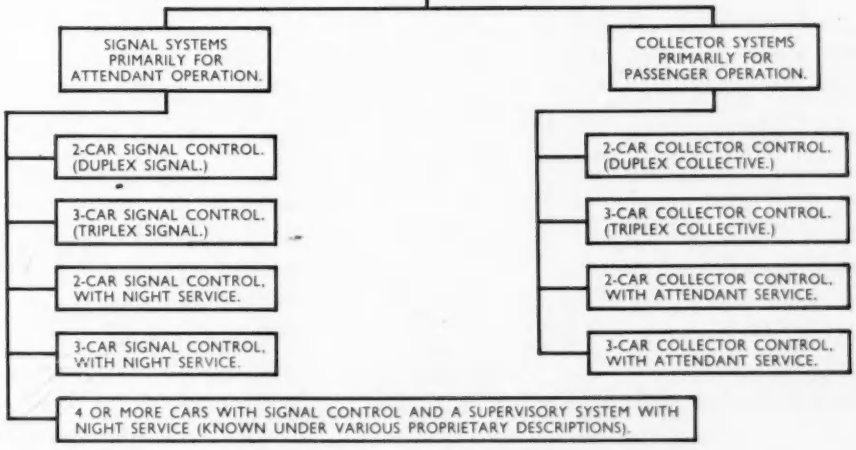
SINGLE CALL SYSTEMS.

Standardised single and multiple call controls are shown in diagram 3. Before studying this diagram, the present-day requirements of single call controls will be analysed.

Very few will deny that car switch control is not nearly so popular as it was, say, twenty years ago. On the other hand, automatic control operated by attendants as well as by passengers is gaining in popularity. This is a perfectly natural development. The operation of automatic lifts is now very reliable and the equipment

DIAGRAM 2.

EXISTING CONTROL SYSTEMS FOR TWO OR MORE CAR INSTALLATIONS.

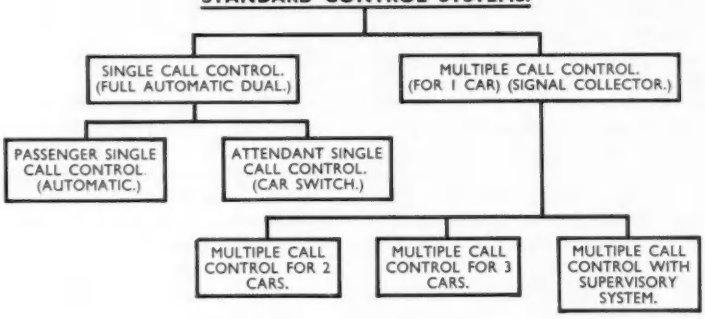

SIGNAL SYSTEMS PRIMARILY FOR ATTENDANT OPERATION.
COLLECTOR SYSTEMS PRIMARILY FOR PASSENGER OPERATION.
2-CAR SIGNAL CONTROL. (DUPLEX SIGNAL.)
3-CAR SIGNAL CONTROL. (TRIPLEX SIGNAL.)
2-CAR SIGNAL CONTROL. WITH NIGHT SERVICE.
3-CAR SIGNAL CONTROL. WITH NIGHT SERVICE.
2-CAR COLLECTOR CONTROL. (DUPLEX COLLECTIVE.)
3-CAR COLLECTOR CONTROL. (TRIPLEX COLLECTIVE.)
2-CAR COLLECTOR CONTROL. WITH ATTENDANT SERVICE.
3-CAR COLLECTOR CONTROL. WITH ATTENDANT SERVICE.
4 OR MORE CARS WITH SIGNAL CONTROL AND A SUPERVISORY SYSTEM WITH NIGHT SERVICE (KNOWN UNDER VARIOUS PROPRIETARY DESCRIPTIONS).

The basic equipment for all Signal and Collector Systems is identical.

The fine distinctions will be apparent between Signal Control with Night Service and Collector Control with Attendant Service when used for 2- and 3-car installations. There are 9 existing systems shown.

DIAGRAM 3.

STANDARD CONTROL SYSTEMS.


SINGLE CALL CONTROL. (FULL AUTOMATIC DUAL.)
MULTIPLE CALL CONTROL. (FOR 1 CAR) (SIGNAL COLLECTOR.)
PASSENGER SINGLE CALL CONTROL. (AUTOMATIC.)
ATTENDANT SINGLE CALL CONTROL. (CAR SWITCH.)
MULTIPLE CALL CONTROL FOR 2 CARS.
MULTIPLE CALL CONTROL FOR 3 CARS.
MULTIPLE CALL CONTROL WITH SUPERVISORY SYSTEM.

The simplification of the standard control systems is immediately apparent when the above 7 controls are compared with the total of 17 existing systems shown in diagrams 1 and 2.

required can be quite simple and easily maintained. It is also obvious that when a car switch lift starts a journey, the attendant knows to which floor he intends to travel. It is much easier momentarily to press a push for that floor than to hold a car switch over in the correct direction until just the right moment of release. This is especially so in modern passenger cars with solid doors. The attendant then has to judge the right moment for releasing his car switch by carefully watching a car position indicator.

It may be contended that with a car switch the attendant can change his mind about that original floor destination at any time before he releases his car switch. It is quite easy to introduce the same facility into a push button operated lift. While the car is travelling, the pressure of another floor push can be arranged to cancel the first destination and substitute the second, provided the car has not already passed the point at which it must slow down in order to stop at that floor. This added facility has the effect of converting the service given by a modified or semi-dual control to that of a car switch dual or full dual control.

The single call control would always have a full set of floor pushes in the car, also a call indicator with a transfer switch. The lift could be operated by pushes, with or without an attendant, and in each case the service given would be equivalent to that of a car switch or automatic lift, but in the case of operation with an attendant less skill would

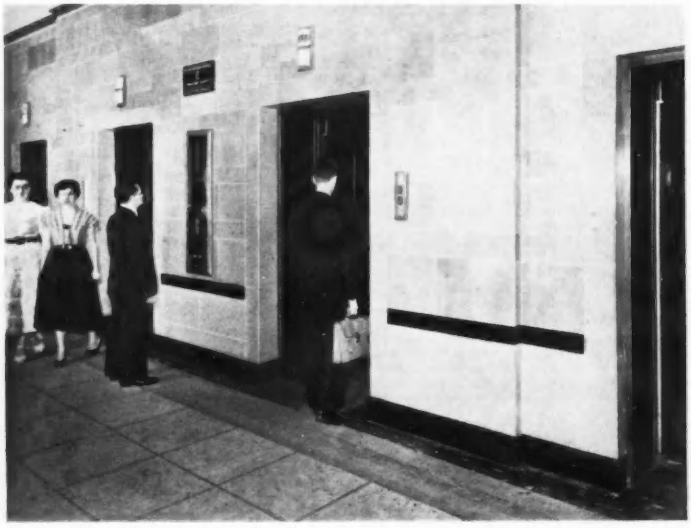


Fig. 5.—A bank of four lifts in an important city office block. Multiple call control with supervisory system is used.

be required, as the attendant would be using floor pushes instead of a car switch.

Many factory managements do not favour a vertical transport system which ties an attendant to a lift for the whole day. They prefer any one of a number of employees to be able to use the lift when necessary, but they require the lift to give the service of an attendant-operated lift when in use, so that landing calls are registered in the car. This is quite simple if the driver just pushes floor buttons instead of having to be trained to use the car switch. The cost of such an attendant-operated lift is greater than that of the old car switch type, but with modern floor selection equipment the extra is not much and is generally considered well worth while.

Once this type of push button control is accepted, it will be realised that all the equipment is present for the ordinary passenger type of operation. Many lifts have been installed with car switch control, and then, due to a change in labour conditions, have had to be altered to dual control.

The cost of a single call control lift is very little more than that of a simple automatic lift, but is much more flexible in operation. This

Figs. 6 and 7.—Combined indicator and service control panel for a bank of three lifts using multiple call control for three cars. The top panel indicates all the cars' movements and the location of landing calls. The lower panel can be opened by the supervisor so that he can make the necessary adjustments to the service of the lifts. Note the cableform and terminal blocks made accessible by opening the top panel.

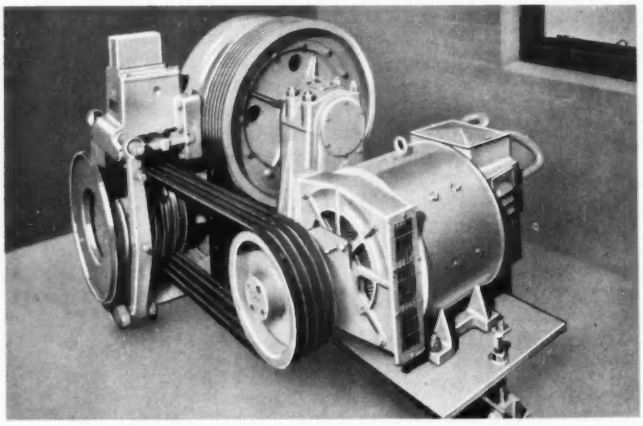


Fig. 8.—The geared machine of a medium speed office lift with variable voltage motor and worm reduction gearing.

system is now available and is sold under the description "full automatic dual control", so as not to make too violent a break with the orthodox type of name.

It is accepted that in certain special cases, as, for example, the installation of a large number of lifts in subsidised municipal flats, where the type of operation will obviously never need to be changed, and where the first cost is of paramount importance, the single call system should be used without the small extra cost required for the facility of changing from passenger to attendant operation. Such a system would be known as passenger single call control and is, of course, the old automatic control. There would probably be some demand for this small saving in cost on some goods lifts and small office lifts. It is only the car indicator and transfer equipment that is saved.

There might also be a demand, for a time, for the simple goods lift operated by a car switch or continuous pressure "up" and "down" buttons in cases where the lift is not often used. The speed in this case is very low and someone is easily trained to use the lift when required. This system is merely a further restriction of the flexibility and easy operation of the normal single call lift and would be known as attendant single call control. Unless a car position indicator is required, the whole of the floor section equipment is saved, also floor pushes in the car.

A two-floor lift with "up" and "down" buttons in the car is still a true single call lift with very simple equipment, by reason of the small number of floors it serves.

MULTIPLE CALL SYSTEMS.

From what has already been said, it will be realised that the grouping together of signal and

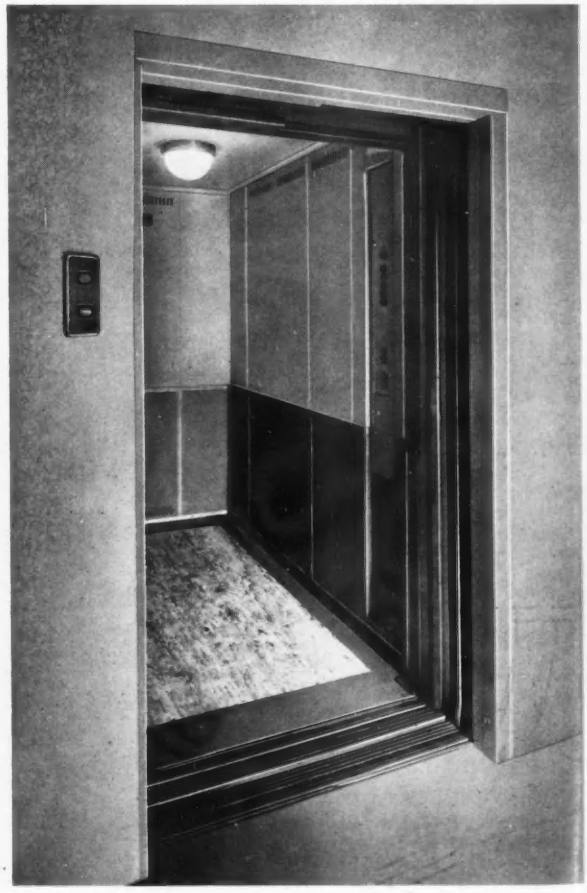


Fig. 9.—The entrance and car of a hospital lift using a single call control.

collector control with their combinations of dual systems, is already an accomplished fact so far as equipment is concerned. The continuation of the various distinctions is artificial, and even if it has sales value, it has no benefit for the owner or the designer who is trying to standardise to the advantage of both maker and user.

It may be possible to purchase collector lifts more cheaply than signal lifts, and similarly collector with attendant service more cheaply than signal with night service, or vice versa, whereas the difference in essential equipment is more imaginary than real. If there is an appreciable difference in the equipment used, it must be due to its inherent inflexibility.

It is also a fact that this type of lift increasingly requires the dual feature. Consider the lifts in a busy office building: if they are installed for attendant operation only, the whole activity of the building can be paralysed by the absence of the attendants. The dual feature eliminates this contingency. For this and other reasons the old idea of one only of a group of signal lifts being capable of giving a service without an attendant, is obsolete. It should be possible for the whole group to be able to give such a service.

It is not surprising therefore that the multiple call system is now available, but again, out of deference to traditional practice, it is known as signal-collector control.

In a group of multiple call (signal collector) lifts, any of them can be operated with or without attendants. In a group of, say, three lifts, at the same time two can be operated with an attendant and the third without, or vice versa, as well as all on attendant operation or all on passenger operation. The owner has thus got an installation of maximum flexibility right from the start, without the danger of finding at a later date that his installation has too rigid a control system, and this at a price little, if anything, above that for signal or collector control.

Multiple call lifts can operate on a one, two, three or more car system, i.e. there can be a multiple call control for one car, two cars, and so forth. The landing call system is common for a group of lifts and the control system directs the cars in answer to the landing calls so that they are reasonably spaced. By this means, the waiting time of potential passengers is evened out to a low average, but at the same time car passengers are given a certain amount of preference in the matter of starting the cars from the main parking floor.

There are a number of features which should be common to all multiple call lifts. One of these is what is often termed " highest call reversal ". It means that a car will not necessarily go to the top of its possible travel. It will only go as far as the highest call registered before reversing its direction of travel.

Another feature is the postponement of landing calls so that they cannot stop the car when it is already full. When this feature is used, the landing calls automatically become effective again as soon as the car has stopped for the next car call. The assumption is, of course, that the car has stopped to unload some passengers and so is no longer full. On attendant operation, this feature is used by pressing a pass push. On passenger operation, the feature can be effective by automatically weighing the load in the car. Since many multiple call lifts are only used without attendants when the traffic flow is very small, the likelihood of the cars getting full is slight and the extra expense of the automatic weighing device is not required.

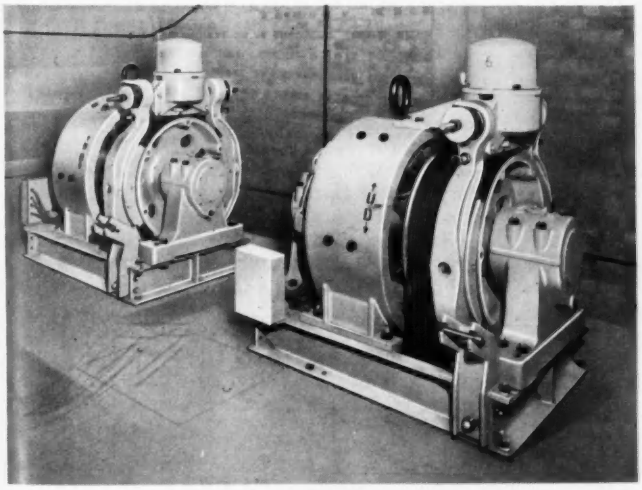


Fig. 10.—The gearless machines for two high-speed lifts interconnected with a multiple call control for two cars.

SUPERVISORY SYSTEMS.

The service given by single call passenger-operated lifts has been likened to a " taxi "

service, since it only caters for one call at a time. However, once the taxi (in this case the lift car) has been obtained, then the passenger can be sure of being taken straight to the correct floor without any regard to the requirements of other potential passengers. The service of a multiple call lift can be likened to that of a " bus ". The bus will keep stopping on the way for waiting passengers as long as it has some spare capacity. When a fleet of motor buses is in operation along the same route, some additional control is required to ensure an efficient service. The buses are made to run to a time-table or schedule.

Banks of lifts with several cars can be likened to a fleet of motor buses. Such groups of lifts have many control features in common, in spite of the brilliant assortment of names used by the few makers of these highly developed examples of the art. They are all basically multiple call (signal collector) lifts with controlled despatch from the parking floors. The object of the controlled despatch is to space the cars so as to regularise the service given to each floor in each direction of travel, or to meet the special traffic flow of a particular time of the day. There are a great many variations in the methods used for altering the despatch of cars according to the traffic needs at the moment. For instance, the cars are despatched to high and low zones of the floors served, for increasing the efficiency under certain traffic conditions.

Whatever the name of the control, it can be regarded as a supervisory system for automatically despatching the cars from parking floors and restricting the floors served. Hence, there appears to be good reasons for using the term " supervisory control ". At the same time, it is clearly understood that the supervisory system is applied to a group of multiple call lifts.

There is a growing need for automatic supervisory systems. Problems of varying traffic conditions arise at different times of the day. The lifts must therefore be able to adapt themselves to meet these conditions with as little human supervision as possible.

In the majority of buildings, there are three major types of traffic conditions: first, the " up peak " period when people come to work in the mornings ; second, the " off peak" period, during the greater part of the day, when there is normal two-way traffic ; third, the " down peak " period when people are leaving the building in the evening.

It can also be contended that there are three minor types of traffic conditions. Two of them can be encountered during the midday period and are sometimes regarded as a variation of the " off peak " period. As the greater number of people are leaving the building for lunch, there will be a " heavier down " period, and after lunch this will be reversed by a " heavier up " period. After business hours, the very much reduced lift service required can also be regarded as a night service period.

It is natural that the amount of automatic supervisory control required will vary with the type of building and the size of the installation. The greater the number of cars and number of floors served, the more essential it is to control the movements of the cars according to the predominating direction of traffic flow. This can all be summed up by stating that the supervisory control, if automatic, should be designed to adjust the operation of the lifts according to the density and direction of calls. All shades of peak periods will then be catered for, whatever their type. In other words, just another case of simplification.

CONCLUSION.

This simplified system of controls for electric lifts can be brought about by a little co-operation between purchasers and manufacturers, to the benefit of both parties. Very often the purchaser is confused by the variety of systems offered to-day at an equal variety of prices. Instead of having to weigh up carefully all the subtle differences and accurately forecast his probable requirements extending over the life of the lift, the prospective owner is offered a choice of two main systems, i.e. single call control or multiple call control, and the distinction between their operation and price makes it easy for him to select which he wants. In addition, having made his choice, the owner will find a reasonable degree of flexibility in either system which will cover any normal change in the manner of operating the installation.

It is hoped that this standardised system of controls for electric lifts will be considered in official circles, as its adoption cannot do otherwise than promote a much-needed measure of rationalisation. Finally—and what is, perhaps, more important than all else—in the export market standardisation of products and clarification of sales literature are essential for success.

Variation of the Physical Properties of Glass with Time in the Transformation Range

By R. W. DOUGLAS, B.Sc., F.Inst. P.
G.E.C. Research Laboratories.

INTRODUCTION.

AN understanding of the physical behaviour of glass requires a knowledge of the way in which the component atoms are arranged and of the forces acting between the atoms. It can be shown that the characteristics of glass can best be understood if the material is regarded, not as a solid, but as a liquid, albeit one of very high viscosity.

In general, the densities of the liquid and crystal solid forms of the same substance are very similar. It therefore follows that the change from the crystal to the fused form has not changed the atomic structure by very much, and the atoms in the substance are still about the same distance apart. We know that the structure of a crystalline solid has long-distance order, the atoms being arranged in definite patterns or lattices. This order is actually suggested by the outer habit of the solid and is confirmed by X-ray diffraction studies. There is, however, a complete contrast between a crystal with its beautiful external symmetries and a liquid which takes the shape of any vessel into which it is poured. The high degree of disorder of the atoms in a liquid is reflected, on a larger scale, from its flowing properties. Again, the X-ray diffraction patterns obtained from liquids confirm this lack of order.

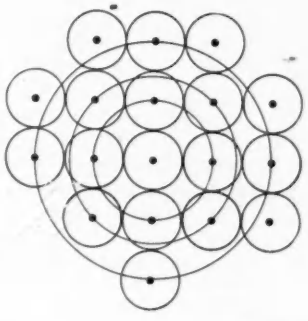


Fig. 1.—Schematic diagram showing regular array of atoms as in a crystalline solid.

ATOMIC STRUCTURE.

Figs. 1 and 2 show the essential difference between the positions of atoms in a crystal and in a liquid on a two-dimensional scale. In fig. 1, all the atoms are arranged in a regular lattice. Each one is therefore surrounded by the same number of "nearest neighbours," "next nearest neighbours" and so on. In fig. 2, an attempt has been made to keep the atoms at approximately the same distance apart, in order to preserve the essential density relationship with solids, and yet to introduce some disorder into the pattern.

Taking any one atom in fig. 2 as a starting

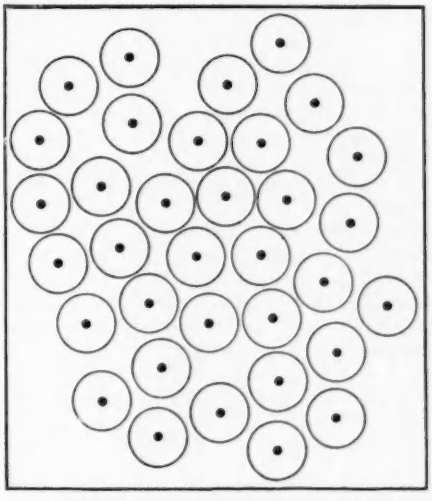


Fig. 2.—Arrangement of atoms in a liquid.

point, it can be seen that there is an immediate circle round it containing about six other atoms, and then a further circle that contains about ten other atoms. It is therefore possible to talk of nearest and next-nearest neighbours in the atomic structure of both liquids and crystals. Since the various sets of neighbour atoms in the liquid seem to be arranged according to some fixed law which gives the probability of finding an atom at a given distance from the centre atom, the arrangement in fig. 2 can be described graphically even though it has a certain randomness or degree of disorder.

Consider for a moment a gas instead of a liquid. In a gas the atoms are a long way apart and are continually moving from place to place. If an observer could watch a particular element of volume in space, every now and again there would be an atom in this volume, thus for a certain part of the time this volume is occupied. If this time for which the volume is occupied is divided by the total time for which the observation is continued the quotient will represent the probability of a point being occupied whenever an observation is made. Now in a gas the atoms are continually moving and there is no reason why the probability of occupation should vary from point to point. Let this constant probability be ρ per unit volume, then if a given atom is chosen as centre, the number of atoms $n_{(r)}$ between spheres of radii r and $r + \Delta r$ will be : $n_{(r)} = 4\pi r^2 \rho \Delta r$.

Thus as r changes, keeping Δr constant, $n_{(r)}$ traces out a parabola.

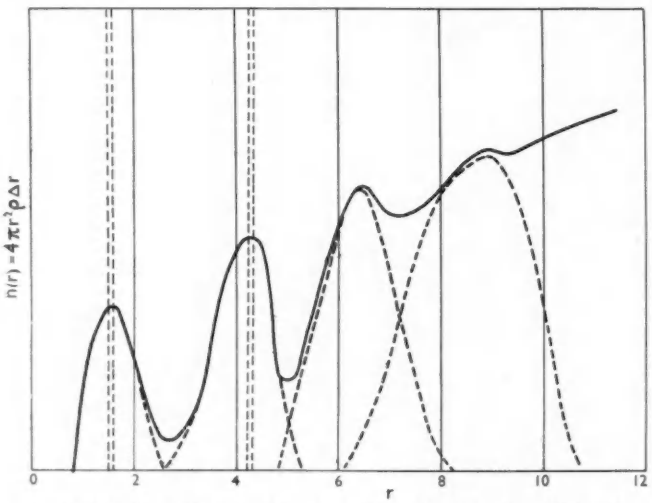


Fig. 3.—The figure illustrates how the distribution curve for a liquid arises. The vertical lines represent the distribution in a hypothetical crystal.

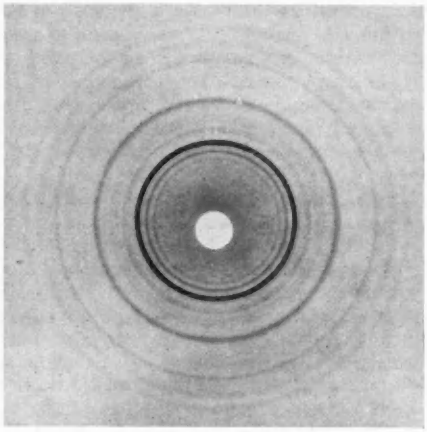


Fig. 4.—X-ray diffraction pattern of barium strontium calcium carbonate.

By contrast in a liquid, where the atoms are much closer together, ρ will not be constant. There will, for example, be no neighbour atoms until the first circle of fig. 2 is reached. When this is reached, ρ will be large but it will then fall to a low value and then rise again when the second circle is reached. At great distances, however, this approach to short range order will have disappeared and it will no longer be possible to define circles on which groups of atoms lie. At great distances therefore ρ will be constant as in a gas. The curve of $n_{(r)}$ for a liquid will thus tend to be a parabola for large values of r but will have a series of a maxima at smaller distances. Such a curve is said to represent the " distribution function " for a liquid.

DISTRIBUTION FUNCTIONS.

The type of distribution curve to which the discussion has led so far is illustrated by the full line in fig. 3. The dashed lines indicate an alternative point of view. Consider the circle of first nearest neighbours. The radius of the circle is r_1 but the actual distances r_a are a little less or a little greater than r_1. The values of r_a could therefore be said to be subject to a certain variability. If a large number of nearest neighbours distances in the liquid could be measured at any one instant

and then n, the number, plotted against r_a, a distribution curve similar to that which represents, say, the distribution of height in a population would be obtained. The dashed lines then represent such distribution curves for the first, second, third and fourth nearest neighbours. The full line of fig. 3 should be obtained by adding the dashed curves together. If the curve is "normalised," i.e. the scales are properly adjusted, the area under the dashed curves will give the number of nearest neighbours of that particular order.

The distribution curve for a crystal would have to be represented by a series of very narrow rectangles at the various interatomic distances. These are also indicated by the dotted lines in fig. 3. As the rectangles would have to be sufficiently long for their area to represent the number of neighbour atoms, it is clearly not convenient to attempt to put the distribution functions for a crystal and a liquid on the same diagram.

The contrasting structures of solids and liquids can again be seen if their X-ray diffraction patterns are compared. Fig. 4, which gives the ring photograph for solid barium strontium calcium carbonate, consists of a series of well-defined concentric rings, each corresponding to one interatomic distance. In contrast, an attempt to obtain a similar picture for liquid barium strontium calcium carbonate leads only to a vague blurred series of rings, which are so ill-defined that precise information regarding the distances between atoms can be obtained only by considerable mathematical analysis. When this analysis is carried out, it enables the distribution function to be determined from the experimental observations. Typical curves so obtained are given in fig. 5.

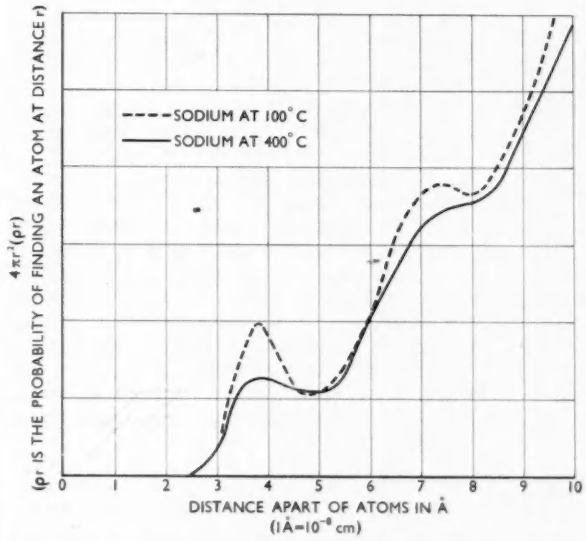


Fig. 5.—Distribution curves for liquid sodium at two temperatures.
(After F. H. Trimble and N. S. Gingrich, "Phys. Rev." (1838), 50, 278.)

ENTROPY AND RANDOMNESS.

Fig. 5 shows that the tendency of nearest neighbours to be found at a constant distance is far more marked at 100 deg. C. than at 400 deg. C. In other words, there is a much greater degree of randomness or disorder at the higher temperature.

An increase in the temperature of any material is a sign that it has been given energy in the form of heat. Internally, the effect of increasing the energy content has been twofold; the average distance between the atoms has been increased, and the disorder of their arrangement has also been increased. This disorder or randomness is associated with the entropy content of the liquid.

CONFIGURATIONAL ENTROPY.

In order to indicate how entropy is associated with randomness, let us consider a very simple model in which a number of particles is arranged along a line. The disorder of the liquid could be represented in this simple model by allowing the distances between the particles to vary about a mean value according to some law such as that represented by the dashed lines in fig. 3. To simplify the problem still further, this disorder may be reduced to allow the distance between a pair of atoms to have one of two values as shown in fig. 6; this is equivalent to an atom being missing every now and again from the regular array.

If there were a large number of atoms, N, and a small number of gaps, n, it will be sufficiently accurate to say that the two atoms next to a gap (A, A) have the average energy E_A and the other atoms have, on the average, energy E_B.

The total energy possessed by the atoms due to these forces is then

$$(N - 2n)E_B + 2nE_A \quad (1)$$

But in order to find whether a

system is in equilibrium the free energy F has to be considered. This is equal to the difference between the internal energy H and the product of the temperature T and the entropy S

$$F = H - TS \qquad (2)$$

The n gaps may be chosen in many ways, for example the first gap might occur between the sixtieth and the sixty-first atom or between the fifteenth and sixteenth. The number of ways of choosing the n gaps will be the same as the number of ways of arranging N particles in $N + n$ boxes. This is derived as follows : The first particle may be placed in any one of the $N + n$ boxes and for each of the $N + n$ ways of placing the first particle there are $(N + n - 1)$ ways of placing the second, and so on. The total number of ways of arranging the particles is therefore

$$(N + n)\,(N + n - 1)\,(N + n - 2)\ldots\ldots$$
$$(N + n - (N - 1)\,) = \frac{(N + n)!}{n!}$$

But if all the particles are alike, we shall, in this product, have counted many identical arrangements as distinct ones ; to allow for this the number of ways must be reduced by dividing by $N!$

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Fig. 6.—Illustration of the disorder in a "monatomic linear" liquid.

ENTROPY OF ENERGY DISTRIBUTION.

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It is important to realise that the entropy factor associated with the distribution of energy is obtained in the crystalline as well as in the liquid state. Only the configurational entropy term is exclusively present in liquids. When a liquid is being considered, the numbers of the two types of arrangements should be multiplied in order to obtain the maximum number of ways in which the distribution of the energy among the atoms, and of the atoms in relation to each other, can be realised. Since, however, the entropy factor is logarithmic in each case, the two entropies $k \log W_C$ and $k \log W_E$ are added where W_C is the number of configurational arrangements.

PHYSICAL PROPERTIES.

Many of the typical differences between the physical properties of a liquid and a solid can be understood by consideration of the configurational entropy. This factor will play its part

in determining all the physical properties of a liquid; symbolically we may write :

$$P_{liquid} = P_{crystal} + P_{config}$$

Expressed in words this means that any physical property, P, may be regarded as made up of contributions from processes similar to those occurring in a crystal, *plus* extra processes due to configurational changes. Taking the coefficient of thermal expansion as an example, that of a solid arises from the increased amplitude of vibrations of the atoms in the crystal as the temperature increases. Each atom needs more room in which to vibrate about its position in the lattice, so that the substance as a whole has to expand. In a liquid, the atoms increase their amplitude of vibration and, in addition, the positions about which they vibrate change and cause an additional increase in volume. One would therefore expect the coefficient of thermal expansion of a liquid to be greater than that of the corresponding solid, and this is generally found to be so.

VARIATION OF PHYSICAL PROPERTIES WITH TIME.

Thus far, we have only considered the movement in space of the atoms in a liquid, but it is clear that this movement cannot be instantaneous, so that the time factor must also be considered. In fact, fig. 5 gives the distribution of the atoms in liquid sodium averaged over both time and space. Now the X-ray diffraction picture of glass at room temperature (fig. 7) is very similar to that of a liquid, in spite of the fact that the material is outwardly a solid. From the macroproperties of a solid, we can deduce that the configuration of the atoms must be fixed and that they must be vibrating about fixed positions, so that fig. 7 gives the distribution averaged over space only. Its similarity with fig. 5, however, strongly suggests that any unusual phenomena associated with the physical properties of glass may be explained in terms of the theoretical treatment of liquids which has been given above.

The complicated distribution curve of fig. 7 can be shown to be due to the fact that the forces holding the atoms together are directed in space so that the glass cannot be considered in the same way as a simple liquid as a collection of spherical particles. Each silicon atom is situated at the centre of a regular tetrahedron, surrounded by four oxygen atoms situated roughly at the corners. Each oxygen atom is shared between two silicon atoms so that a continuous network of silicon-oxygen links is formed. In a simple sodium silicate glass, the sodium atoms are placed in holes in this network.

When glass is heated it begins to flow but it is found that, even at the melting temperature, the liquid retains an extremely high viscosity. The viscosity never falls much below 10,000 times that of water, and this property suggests that changes in the configuration of the atoms in the liquid glass are taking place rather slowly compared with those occurring in other liquids.

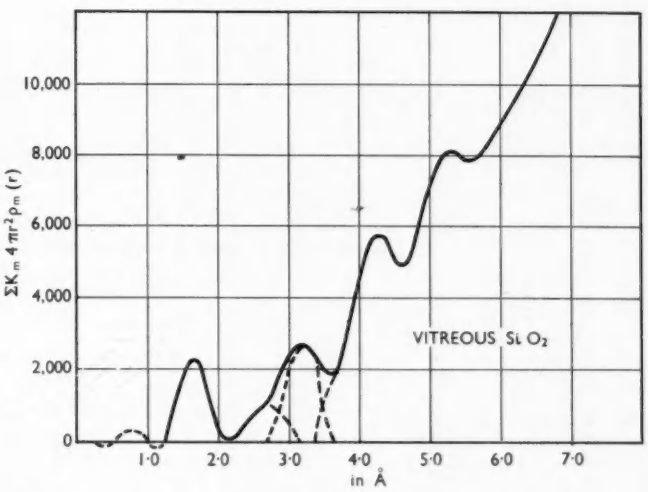

Fig. 7.—The radial distribution curve for vitreous silica. (*After B. E. Warren, H. Krutter and O. Morningstar.*)

On cooling, the viscosity of the glass increases and this may be attributed to the fact that the atoms find it more and more difficult to move about relative to one another. It may be deduced therefore that, as the temperature drops, the time taken for the atoms to reach the equilibrium configuration suitable for each new temperature gets longer and longer. Eventually a temperature will be reached at which the time taken to reach equilibrium is long compared with the time taken to make an observation of the normal kind. Here then a repeat measurement will give a different result because the configuration will have changed since the first experiment was made. The physical properties will now appear to be changing

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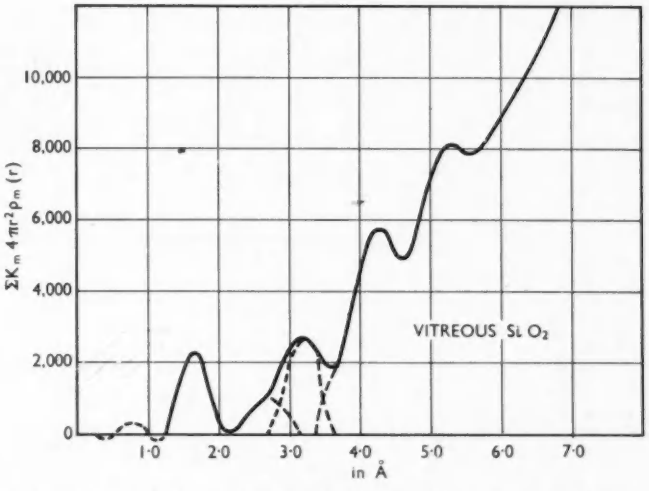

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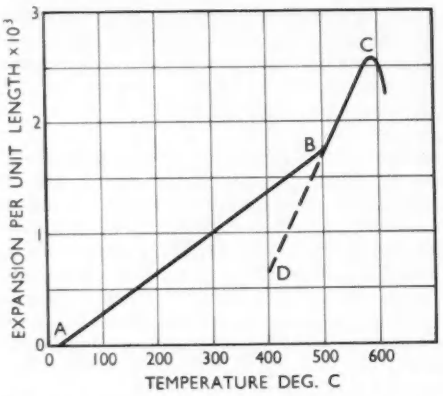

Fig. 8.—Curve of thermal expansion for W1 glass.

with time at constant temperature.

It can be shown that there is a certain range of temperature over which these changes in the physical properties with time can be measured. The range is conveniently referred to as the transformation range. Above the transformation range, the atoms take up new configurations suitable to the changing temperature very rapidly, and the change in physical properties follows the temperature without any time lag. Below the transformation range the changes in configuration would take so long to occur that, practically, they may be said not to take place. We can regard the structure as being that appropriate to a higher temperature but "frozen in" at a far lower temperature, and no changes in the physical properties will be observed however long the time taken for the observations.

These three temperature ranges can also be regarded in terms of the equation,

$$P_{liquid} = P_{crystal} + P_{config.}$$

given earlier. Above the transformation range, the two right-hand terms act simultaneously. In the transformation range the changes in physical properties with time are due to the fact that $P_{config.}$ comes into operation slowly, and below the transformation range $P_{config.}$ remains constant at all temperatures.

Four of the physical properties of glass will now be discussed in the light of the foregoing discussion.

THERMAL EXPANSION.

*Fig. 8 gives the thermal expansion curve for a borosilicate glass (G.E.C. W1), the full line giving the results obtained from the normal method of measurement. As the temperature increases, the thermal expansion is approximately linear between *A* and *B* but is then

* R. W. Douglas and G. A. Jones, *J.S.G.T.* (1948,) *32*, 309.

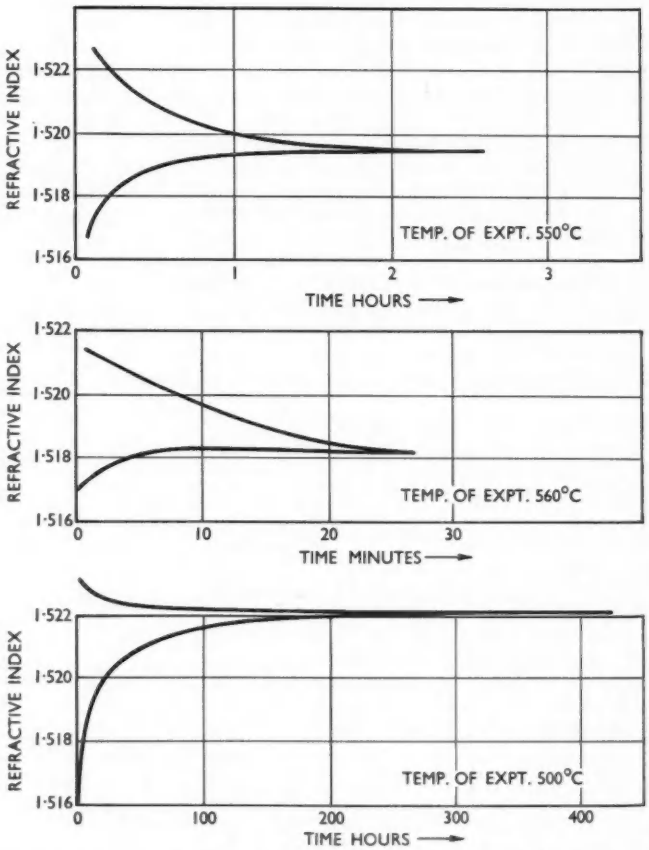

Fig. 9.—The approach to equilibrium configuration: changes in refractive index. (*After A. Winter.*)

followed by a sudden increase above *B*. In the light of the present discussion, this is explained by the fact that the configuration cannot change, i.e. takes too long to change, below B and so we have only the contribution $P_{crystal}$ to the expansion. Above *B*, it is suggested that the configuration can change with time, giving rise to an increased thermal expansion because the configurational change is sufficiently rapid to cause a measurable change in volume during the measurement. (The dip at *C* is merely due to the softening of the glass under the pressure of the apparatus.)

If one could therefore repeat this experiment, taking thousands of hours over it, one would expect the effect of the configurational contribution to begin at a much lower temperature. This precise modification of the experiment has not been done, but the density of the glass was determined at a series of temperatures in the transformation range after it had been heated long enough at each given temperature to reach equilibrium. From the equilibrium densities so obtained, the " equilibrium " thermal expansion may be calculated. This is shown dotted in fig. 8. It is immediately apparent that, by taking a very long time over the experiment, the apparent transformation point which was originally at 500 deg. C. could be reduced to about 400 deg. C. The figure makes it clear that, provided sufficient time has elapsed, the configuration changes can make their full contribution to the thermal expansion of the glass at lower temperatures.

REFRACTIVE INDEX.

Other physical properties of glass, when measured over a long time in the transformation range of temperature, should also lead to a similar conclusion. The aim is to show that any change of temperature within this range results in a slow creep towards the equilibrium temperature appropriate to the new temperature. Experiments on changes in refractive index carried out by A. Winter (*Jour. Amer. Ceram. Soc.* (1943), *26*, 193) resulted in the graphs shown in fig. 9. Two samples of glass were placed in a furnace at constant temperature ; one had been cooled quickly from the molten state, and the other had been held for many hours at a temperature some tens of degrees below that at which the experiment was performed. At intervals the samples were removed from the furnace and their refractive indices measured at room temperature. In a separate experiment two specimens, both of which had previously received the same heat treatment, were held at constant temperature, one only being removed from the furnace at intervals for measurement. When finally both were removed, they were found to have the same refractive index. This confirmed that the experimental procedure was justified, since successive

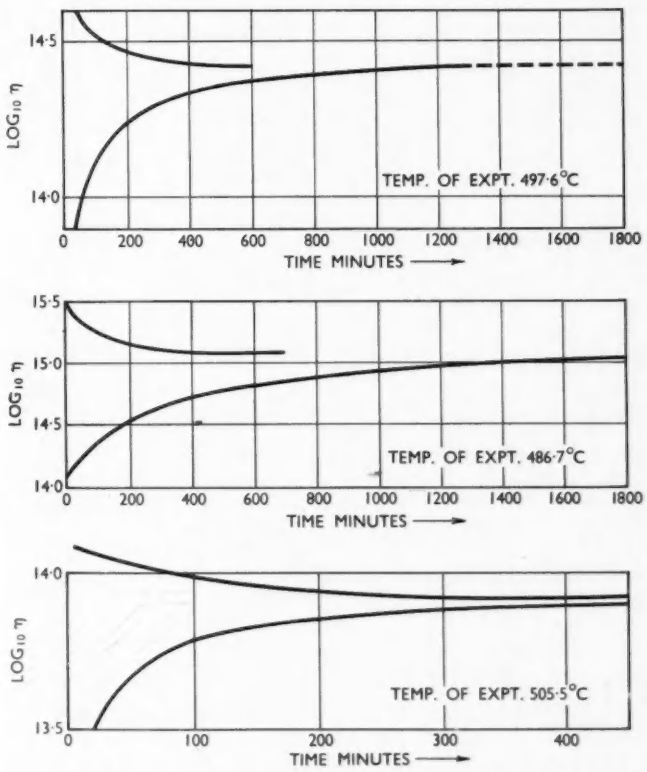

Fig. 10.—The approach to equilibrium viscosity. (*After H. R. Lillie.*)

cooling and heating had no effect on the results.

In fig. 9, the upper curve of each pair refers to the specimen preheated at a temperature below that of the experiment. The lower curve is for the specimen cooled rapidly from some higher temperature. The series of three curves shows that, at each temperature, the refractive index has a unique value which is approached more slowly as the temperature of the experiment is reduced. At 560 deg. C. the time taken is about 27 minutes, at 550 deg. C. it is 2½ hours and at 500 deg. C. it has increased to over 200 hours. The experiments further suggest that the equilibrium configuration for each temperature, as reflected in the physical property measured, is independent of the previous history of the specimen.

VISCOSITY.

The qualitative relationship between the viscosity of a glass and its temperature has already been mentioned. Quantitative results similar to those given above for the refractive index were obtained by H. R. Lillie (*Jour. Amer. Ceram. Soc.* 1933, *16*, 619) and are given in fig. 10. The viscosity of glass fibres " as drawn " was measured and is given as the lower curve of each pair. After the fibres had been stabilised at temperatures below that at which the viscosities were measured, the upper curve was obtained. Again, the time taken to reach a steady value for the property measured increases with decreasing temperature.

SPECIFIC HEAT.

The heat absorption of a glass in the transformation range also leads to a similar conclusion about the time taken for the configuration contribution to act. Fig. 11 was obtained by A. Q. Tool and C. G. Eichlin (*Jour. Amer. Ceram. Soc.* 1931, *14*, 276), who heated glass in granular form at a constant rate together with alumina granules. The difference in temperature between the two substances was measured, each experimental run relating to a glass which had previously received a different thermal treatment. Curve *A* relates to a glass chilled from 620 deg. C. and shows that the material gave out heat at about 320 deg. C. This is due to the fact that the "frozen in" configuration for the glass sample would be approximately that in equilibrium at 620 deg. C., so that heat is given out when the configuration begins to change at a noticeable rate towards the lower temperature equilibria. At the highest point of curve *A*, the glass will have reached a configuration with a free energy approximately the same as that for 410 deg. C. From this temperature up to about 470 deg. C., the glass is trying to change its configuration to conform with the temperature, but since this change is from a state of higher free energy to a state of lower free

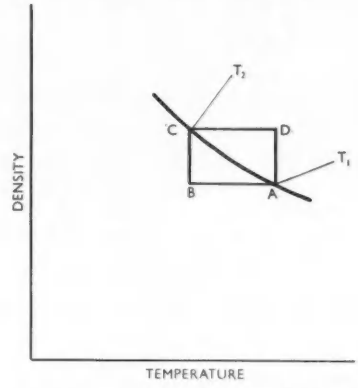

Fig. 12.—" Reversible " changes discussed on a density-temperature diagram.

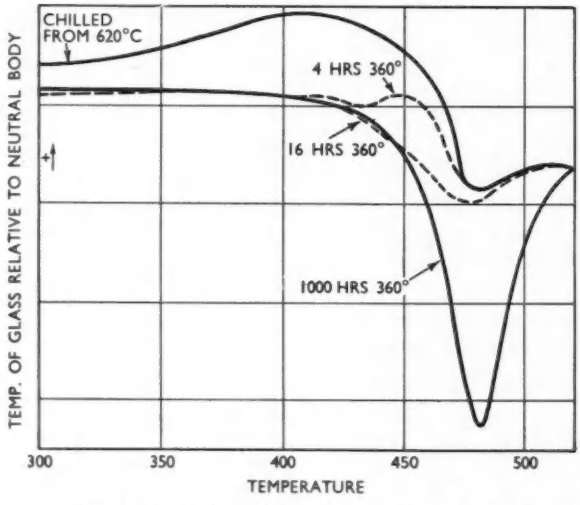

Fig. 11.—The heat absorption in glass subjected to various heat treatments. (*After A. Q. Tool and C. G. Eichlin.*)

energy and does not take place instantaneously, heat is being given off.

Curves *B*, *C* and *D* are for glass which had been heat-treated for various periods (4, 16 and 1,000 hours) at 360 deg. C. The longer the glass is heat-treated at 360 deg. C., the nearer will its configuration be to the equilibrium for that temperature and the greater will be the heat

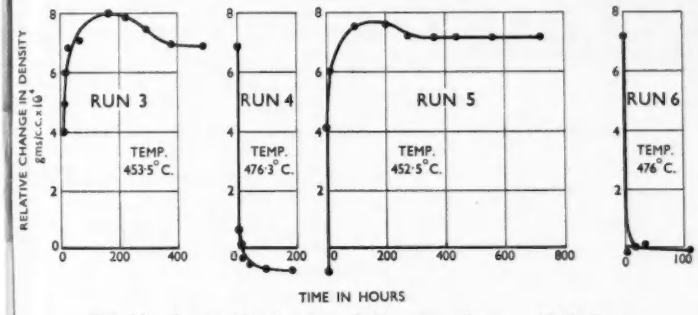

Fig. 13.—Reversible changes of density with time: W.1 glass.

absorption on reheating. The small maximum on curve *B* indicates that some higher temperature equilibrium still remained after only 4 hours' heating time. Above about 480 deg. C., the changes should be practically instantaneous and no further absorption or evolution of heat should be observed. The curves then approach a common value which will differ from that existing before the equilibrium changes began, since the specific heat of the glass will now include the configuration contribution and its temperature will therefore lag further behind that of the alumina in the experiments.

"REVERSIBLE" CHANGES.

All these experimental results therefore tend to confirm the validity of the theoretical approach outlined above. One other verification should be possible, based on the fact that the previous history of the specimen does not affect the results obtained. This leads to the conclusion that configurational changes should be "reversible". In other words, since any change of temperature in the transformation range results in a slow creep towards the equilibrium configuration appropriate to the new temperature, any change back to the first temperature should likewise be accompanied by a creep back to the first configuration. The physical property measured should therefore be capable of going through the cycle in fig. 12. If the glass is at equilibrium at a given temperature (point *A*) and the temperature is then reduced suddenly, there should be a change in property into which only the $P_{crystal}$ contribution has entered (point *B*). Holding the specimen at the lower temperature long enough for $P_{config.}$ to play a part changes the physical property further (point *C*). On raising the temperature again, an instantaneous move to point *D* should take place, and finally point *A* should again be reached after a longer time has elapsed.

The results of an experiment to show this reversible process in the physical property of density are given in fig. 13, which relates to a specimen that had been brought to equilibrium at about 476 deg. C., and was then heated to 453 deg. C., for the times stated on the graphs. It can be seen that there is an initial sudden density change, followed by a slow change approaching equilibrium. As the experiment proceeded, the "bump" in the curve in the earlier graphs disappeared and it is clear that a reversible change in the volume is in fact taking place. This, then, agrees well with the predictions made from the theoretical considerations outlined above.

The occurrence of the "bump" in the early curves was at first surprising and called for further investigation. Fig. 14 shows clearly that the density of the glass, which had been

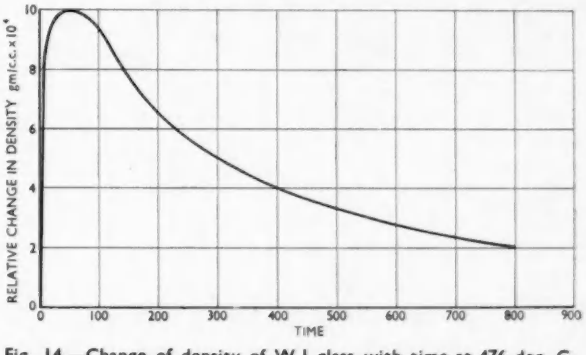

Fig. 14.—Change of density of W.1 glass with time at 476 deg. C., after quenching from high temperature, showing two relaxation processes.

quenched from some quite high temperature and then heated at 476 deg. C., increased over an initial range and then fell off at a much slower rate. This leads to the conclusion that there are two distinct processes which make up the configurational change. The initial rise is due to the normal configuration changes with decreasing temperature which reduces the average distance between atoms. The glass used for the experiment was a borosilicate glass and the second process which leads to a slow decrease in density is associated with a tendency for glass

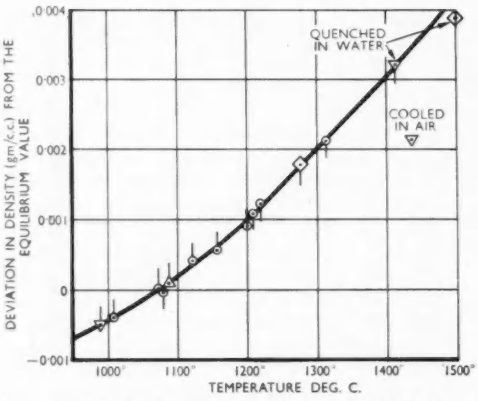

Fig. 15.—Deviation in density from the equilibrium value.

to separate into a silica skeleton interpenetrated by a borate complex.

On repeating the density experiments with fused silica, the curve shown in fig. 15* was obtained. The equilibrium density was measured over a whole range of temperature, using several specimens. The reversibility of the configurational change is well demonstrated by the fact that the results always lie on the same curve, regardless of whether the specimen was heated or cooled to the temperature at which the measurement was taken. The curve again shows a peculiarity in that the density increases with temperature. This is typical of the behaviour of water between 0 deg. and 4 deg. C. and it is believed that the reason is the same. In pure silica the bonding is by strongly directive links and these tend to break down above a certain temperature, causing the structure to collapse so that the atoms get closer together, leading to an increase in density.

* R. W. Douglas and J. O. Isard, "Density Change in Fused Silica," *J.S.G.T.* (1951), *35*, 206.

CONCLUSION.

This article has dealt with only one facet of the physics of glasses, but the processes considered are those responsible for the behaviour which typifies a glass as a special kind of substance. To go further and discuss the differences which exist between the properties of a series of glasses of various chemical compositions necessitates the consideration of the actual bonding forces between the atoms. As a first approximation the glass-forming oxides may be divided into two classes, the network-forming oxides such as SiO_2 and the network modifiers such as Na_2O. Much useful empirical knowledge has been accumulated and discussed in these terms. To go further, considerations of the theory of valence have to be introduced.

Finally it should be pointed out that the emphasis here has been on those physical properties which may be said to arise from the lack of long distance order. It is interesting to note that other physical properties such as colour depend only on the forces between near neighbour atoms and these are usefully discussed in the same terms as similar properties of crystalline materials, i.e. in terms of the approximately ordered arrangements which exist over short distances.

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